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TIME DRIVEN TUNABLE LASER BASED SWITCHING WITH COMMON TIME REFERENCE

RELATED APPLICATIONS:

This is a continuation-in-part application, under 37 C.F.R. §1.53, of pending prior application Serial No. 09/120,700, filed on 07/22/98, for "INTERCONNECTING A SYNCHRONOUS SWITCHING NETWORK THAT UTILIZES A COMMON TIME REFERENCE WITH AN ASYNCHRONOUS SWITCHING NETWORK," and further claims priority of pending provisional application Serial No. 60/235,765, filed on 09/27/2000, for "SWITCHING, GROOMING, AND DEGROOMING METHODS AND LINK TRANSMISSION CONTROL WITH COMMON TIME REFERENCE," and of pending provisional application Serial No. 60/261,133, filed on 01/10/2001, for "SWTICHING METHODS WITH COMMON TIME REFERENCE AND PLURALITY OF TIME FRAME DURATIONS."

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT:

Not Applicable.

BACKGROUND OF THE INVENTION:

This invention relates generally to a method and apparatus for switching and grooming of data units, over a plurality of communications links with a plurality of transmission rates, in a communications network in a timely manner while providing low switching complexity and performance guarantees.

Circuit-switching networks, which are still the main carrier for real-time traffic, are designed for telephony service and cannot be easily enhanced to support multiple services or carry multimedia traffic in their native packet formats. Circuit-switching is based on very accurate clock frequency for byte-by-byte switching. This enables circuit-switching networks to transport data streams at constant rates with a small delay jitter. Finally, the clock accuracy for SONET requires increasingly more accuracy as the lines transmission speed increases.

Packet switching networks handle bursty data more efficiently than circuit switching, due to their statistical multiplexing of the packet streams. However, current packet switches and routers operate asynchronously and provide "best effort" service only, in which end-to-end delay and jitter are neither guaranteed nor bounded. Furthermore, statistical variations of traffic intensity often lead to congestion that results in excessive delays and loss of packets, thereby significantly reducing the fidelity of real-time streams at their points of reception. Finally, current packet switches and routers electronically process the header of each packet to be routed and switched, which requires high processing power and limits the scalability of the packet switching network.

Circuit switches use time for routing. A time period is divided into very small time slices, each containing only one byte. The absolute position of each time slice within each time period determines where that particular byte is routed.

In accordance with some aspects of the present invention, time-based switching/routing supports a more sophisticated and flexible timing than circuit switching. Consequently, time-based switching provides better support of video-based multimedia applications. The time frames used for time-based switching in the present invention has larger time duration than the time slot used in circuit switching – consequently, time-based switching is much simpler than circuit switching. The present invention also supports routing based on control information included in at least one of headers and trailers of selected ones of the time frames, which current circuit switching cannot provide for.

Moreover, the present invention uses Common Time Reference (CTR). The CTR concept is not used in circuit switching. Using CTR has far reaching implications when comparing circuit switching and the current invention. For example, CTR ensures deterministic no slip of time frames, while enabling deterministic pipeline forwarding of time frames. This is in contrast to circuit switching, where (1) there are time slot slips, and (2) deterministic pipeline forwarding is not possible.

In U.S. Pat. No. 5,418,779 Yemini et al. disclose a switched network architecture that uses time. Time is used in order to determine when a plurality of switches can transmit over a predefined routing tree to one destination. This kind of tree is known as "sink" tree since the destination switch functions as a "sink" for the transmission from all switches. The time interval in which the plurality of switches transmits to a selected "sink" destination switch is called time band. In different time bands the plurality of switches are transmitting to a different single "sink" destination switch. Network switches change their configuration between time bands in order to

build the proper "sink" tree during each time band. The present invention does use neither "sink" trees nor time bands for transmission over "sink" trees.

Yemini's invention may not be realizable in communications networks with end-to-end propagation delays that are not much smaller than the time band durations. In general, in Yemini's invention the end-to-end propagation delays introduce a non-trivial scheduling problem that may or may not have a solution. Furthermore, Yemini's invention does not discuss or specify how to take into consideration the link propagation delays and the end-to-end propagation delays. Consequently, general topology switched network cannot be built the way it is taught by Yemini's et al. invention.

Yemini's invention has another problem, which is congestion, that is the direct result of using "sink" trees. Data units received from different upstream switches contend for a single outgoing link towards the root of the "sink" tree. The present invention does not have any congestion. This is a direct consequence of using in the current invention completely different system operation principles and methods.

For example, in Yemini's et al. patent there is no pipeline forwarding: data units do not proceed in a lock-step fashion through the communications network, as it is the case in the present invention. The lack of pipeline forwarding leads to the above mentioned scheduling and congestion problems. Such problems are due to the fact that incoming time bands of Yemini's invention are not aligned in different input ports of the network's switches. Furthermore, it was not specified what are the temporal relationship of the same and different time bands on different "sink" tree switches when the link propagation delay and the end-to-end propagation delay are not zero. In contrast, time frames in the present invention are aligned with a Common Time Reference (CTR) on every switch.

In optical data communications with a single wavelength a single data stream is transduced into a series of pulses of light carried over an optical fiber. These pulses of light are

of a single wavelength. This single wavelength vastly under-utilizes the capacity of the optical fiber, which is capable of carrying a large number of signals each at a unique wavelength. Due to the nature of propagation of light signals, the optical fiber can carry multiple wavelengths simultaneously. The process of carrying multiple discrete signals via separate wavelengths of light on the same optical fiber is known in the art as wavelength division multiplexing (WDM). Many optical components, including, but not limited to, WDM multiplexers, WDM de-multiplexers, star couplers, tunable lasers, filters, waveguide grating routers (WGRs) are deployed in optical networks featuring WDM, and consequently used in the embodiments presented in this disclosure. [T. E. Stern and K. Bala, "Multiwavelength Optical Networks: a Layered Approach," Prentice Hall PTR, Upper Saddle River, NJ, USA, ISBN 020130967X. R. Ramaswami and K. N. Sivarajan, "Optical Networks: a Practical Perspective," Morgan Kaufmann Publishers, San Francisco, CA, USA, ISBN 1-55860-445-6. H. J. R. Dutton, "Understanding Optical Communications," Prentice Hall PTR, Upper Saddle River, NJ, USA, ISBN 0-13-020141-3].

The present invention permits a novel combination of: (1) time-based switching and routing and (2) WDM technology. WDM is including the capabilities for (1) dynamic tunable wavelength transmission, (2) dynamic and static wavelength switching, and (3) tunable wavelength reception.

The increasing demand for communications capacity has led to the deployment of Wavelength Division Multiplexing (WDM), which requires extremely high capacity switches. Lambda or static wavelength *switches* address this need by switching a whole wavelength from an input optical fiber link to an output optical fiber link without requiring any processing of the transmitted data units. WDM with whole lambda_switching will be deployed in the network's optical core. However, switching of whole lambdas (e.g., lambdas of OC-192) is inefficient and costly for three reasons:

1. N square problem: the number of lambdas needed to accommodate all the possible connections among all access points is on the order of the square of the number of such access points. This will limit the size of the optical core.
2. Bandwidth mismatch problem: there is a substantial bandwidth mismatch when extremely high capacity backbone networks feed low capacity access links. As data leave the core and are moved by packet switches towards the edge, buffers at access links frequently become congested, causing increased delays and dropped packets.
3. Traffic unbalancing problem: the traffic load across the network is not evenly distributed, i.e., it is not balanced. Thus, trying to satisfy the traffic load requirements using whole lambda_switching is both inflexible and inefficient.

These three problems are solved by adding the capability of switching_fractions of lambdas or Fractional Lambda Pipes (FLPs). This approach, which is called Fractional Lambda Switching (FLSw), will permit the optical core to be extended much closer to the network edges while reaching the lower speed network access devices with a bandwidth that matches their operation capability.

FLSw dynamically switches lambda fractions while carrying data units (e.g., IP data packets, and SONET STS1 frames), in a heterogeneous (mix of very high speed and very low speed links) meshed network, while providing deterministic performance guarantees. The size of fractional lambda pipes can be dynamically allocated to satisfy the specific needs of the access networks to which a fractional lambda pipe is connected to. Small capacity FLPs can be used at the periphery to access low speed sub-networks, such as, cable modems, xDSL, VoIP gateways and wireless.

Fractional Lambda Switching (FLSw) combines the advantages of circuit switching and packet switching. FLSw is used for constructing a Fractional Lambda Pipe (FLP). A FLP is equivalent to a leased line in circuit switching. A FLP is realized by two simple elements:

1. A Common Time Reference (CTR™) throughout the network that is globally aligned with the Coordinated Universal Time (UTC); and
2. Pipeline Forwarding (PF™) of time frames (logical containers of data packets) across FLPs.

The CTR is a reference clock used to realize pipeline forwarding of time frames, both within switches and across FLPs. The CTR™ is received via the Global Positioning System (GPS), which is globally available at a low cost with an accuracy of 10-20 nanoseconds. The common time reference, or more specifically the UTC second, is partitioned into time frames. The duration of a time frame is a link parameter – fast links might use shorter time frames, while slow links might use longer time frames. Contiguous time frames are grouped into time cycles, and contiguous time cycles are grouped together into contiguous super cycles. The duration of a super cycle is one UTC second, as shown in Fig. 2, and the duration of time frames and the number of timer frames in a cycle can be chosen for convenience. For example, a 1 Gb/s link might use time frames with duration of 125 μs, with time cycles of 100 time frames; while a 10 Gb/s link might use time frames with duration of 12.5 microsec, with time cycles of 1000 time frames. For both links, each time frame will carry the same 15,625-byte payload, and there will be 80 time cycles in each super cycle or one UTC second, as shown in Fig. 2.

The common time reference can be realized by using UTC (Coordinated Universal Time), which is globally available via, for example, GPS (Global Positioning System). By international agreement, UTC is the same all over the world. UTC is the scientific name for what is commonly called GMT (Greenwich Mean Time), the time at the 0 (root) line of longitude at Greenwich, England. In 1967, an international agreement established the length of a second as

the duration of 9,192,631,770 oscillations of the cesium atom. The adoption of the atomic second led to the coordination of clocks around the world and the establishment of UTC in 1972. The Time and Frequency Division of the National Institute of Standards and Technologies (NIST) (see http://www.boulder.nist.gov/timefreq) is responsible for coordinating UTC with the International Bureau of Weights and Measures (BIPM) in Paris.

FIG. 3 shows an example of the pipeline forwarding of time frames, for a FLP™, through switches A, B and C. The path through switches A, B and C has been previously scheduled and no header processing is necessary once the packets enter the FLP. The path between Switch A and B reflects a propagation delay of four time frames (time frame numbers: 2 through 5). The packets are automatically switched to the proper output port of Switch B in one time frame and then forwarded to Switch C, arriving at Switch C after three additional time frames (time frame numbers: 7 through 9). All packets are guaranteed to arrive at the end of their FLP at the same predetermined rate at which they entered the FLP.

Each FLP's switching schedule is simple, and repeats itself every time cycle and/or super cycle. Thus, FLP™, together with the predictability provided by the CTR and pipeline forwarding, eliminate the complexity of data packet header processing. Each FLP™ transports data packets of one protocol, such as IP, MPLS, ATM, FR, or FC. However, each FLP may carry data packets of different protocols.

Fractional lambda switches have significantly lower complexity than packet switches and lower complexity than circuit switches with the same switching capability for the following reasons.

1. Minimum switch fabric complexity that can be implemented using a Banyan network, which has the complexity of $a \cdot N \cdot \lg_a N$ switching elements, where N is the total number of optical channels and 'a' is the size of each switching element.

2. Optimal speed-up with 1 switch fabric – it operates at the same speed as the optical channel (e.g., 10 Gb/s with OC-192 links).
3. Optimal memory access bandwidth that is equal to the optical channel bandwidth – the switch architecture enables that, with only 3 input queues, a queue is never used for reading and writing at the same time, i.e., memory access with a speedup of 1.
4. (Very) small input memory for each optical channel, e.g., a 10 Gb/s channel requires 3 input queues with total of 48 Kbytes of memory, and no buffering is needed on the output port.
5. (Very) simple control of the switch fabric, since its configuration changes at a relatively low frequency (e.g., 80,000 times per second) and it is known in advance. This operation complexity is comparable to that of a T1 multiplexer.

Though highly efficient, a Banyan Network is subject to what is known as switch blocking: it may be impossible to connect an idle input with an idle output because a switching element is not available on the path between input and output. An interesting attribute of fractional lambda switching is the almost complete elimination of blocking through Banyan-based switches.

The advances in optical transport led to the realization of high speed optical channels, however, a single source transmitting to a single destination will not fill such channels. This has led to two basic requirements: (i) Grooming and degrooming: the need to aggregate (i.e., grooming) traffic from multiple sources into one optical channel and to separate (i.e., degrooming) an optical channel traffic to different destinations; and (ii) Dynamic optical switching: the need to route portions from one optical channel (i.e., a lambda or a wavelength) on different optical paths to different destinations.

Dynamic all-optical switching is possible when the optical switch reconfiguration time is significantly smaller than the time between two successive switch configuration changes. Dynamic all-optical switching is appealing for a number of reasons stemming from the transported data stream being transparent to the switching system: (i) intrinsically protocol independent (multi-protocol) transport; (ii) high scalability, since the transmission rate of each optical channel is transparent to the optical switching system; and (iii) no processing performed on switched data units, thus eliminating processing bottlenecks.

The latest advances in optical switching have resulted in decreasing reconfiguration times of optical switch fabrics. However, taking full advantage of such advances for dynamic optical switching is not obvious – for several reasons: (i) Processing of in band control information, e.g., packet headers, is not possible; (ii) Dynamic optical storage is not available to assist in coping with switch control and reconfiguration time; and (iii) Optical switch reconfiguration time should be significantly smaller than the time between two successive reconfigurations.

Due to the above limitations it is not possible to realize an asynchronous packet switching system, and therefore, using time is necessary. However, time-based techniques deployed in circuit switching, e.g., SONET, based on byte switching (i.e., byte de-multiplexing and byte multiplexing), are not applicable to all-optical switches.

The most comprehensive solution to the above-mentioned problems is to use a common time reference (CTR™) for pipeline forwarding (PF™) in order to facilitate dynamic all-optical switching. CTR™ provides the synchronization needed to orchestrate the control of network switches while eliminating the need for optical storage and processing.

Dynamic all-optical switching of time frames – time is divided into time frames, any time frame of a sequence of incoming time frames over one optical channel can be optically switched to any outgoing optical channel. Such time frame switching is the basis of fractional lambda switching (FLSw). FLSw is used for constructing Fractional lambda pipes (FLPs), i.e., fractions

of a wavelength. Each FLP™ transports data packets of different protocols — such as, IP, MPLS, ATM, FR, FC, and SONET frames (e.g., STS1 frame), thereby realizing the desired protocol independent property of all-optical switching.

In an all-optical switch PF™ is realized in two operational phases. Data units belonging to a whole time frame received from each of the optical channels during Phase 1 are switched through the switch in Phase 2. In a possible embodiment, if Phase 1 begins in time frame t, Phase 2 takes place in time frame t+1. In another embodiment, if Phase 1 ends in time frame t, Phase 2 takes place in time frame t+1. The 2 phase operation ensures that data units received from the various optical channels are aligned with the CTR before being switched. Phase 2 can be performed during either the time frame immediately following Phase 1, during time frame t+1 — immediate forwarding operation, or at a later time frame — non-immediate forwarding operation.

Alignment – aligning the beginning and end of each time frame on each optical channel with the beginning and end of the CTR™ time frames. The alignment can be performed either before or after the WDM DMUX.

The alignment is needed since the propagation delay on optical links between switches is not an integer multiple of time frames. The optical alignment system is part of the all-optical fractional lambda switch and operates on all the wavelengths carried by each optical fiber and is part of Phase 1 of the PF™. The optical alignment system is based on a programmable optical delay line guaranteeing that the overall delay experienced through the optical fiber and the delay line is an integer number of time frames. As a result, when data units that have left the switch at the transmitting end of the fiber aligned with the CTR™ arrive at the WDM DMUX at the receiving end are still aligned with respect to CTR™. The alignment system comprises a controller that detects time frame delimiters and adjusts the delay by using a programmable

optical delay line (note that the alignment changes only when the propagation delay on the optical link changes).

Availability of a common time reference (CTR™) on a global scale for all network nodes enables the implementation of dynamic all-optical switches with a simple architecture based on wavelength converters. Since wavelength converters are not available, an equivalent network architecture based on tunable lasers is feasible and presented in this work. This architecture is used to realize fractional lambda switching (FLSw). FLSw is based on a common time reference (CTR™) for pipeline forwarding (PF™) of time frames. In FLSw the synchronization provided by the CTR is leveraged to orchestrate the operation of tunable lasers and/or tunable receivers within a switch and across the whole network.

SUMMARY OF THE INVENTION:

A novel time frame switch fabric control is provided in accordance with some aspects of the present invention, which stores a predefined sequence of switch fabric configurations, responsive to a high level controller that coordinates multiple switching systems, and applies the stored predefined sequence of switch fabric configurations on a cyclical basis having at least one of simple periodicity and complex periodicity. The application of the stored predefined switch fabric configurations permits the switches of the present invention to relay data over predefined, scheduled, and/or reserved data channels without the computational overhead of computing those schedules ad infinitum within each switch. This enables the switch computation unit to operate relatively autonomously to handle new traffic reservation requests without changing the predefined switch fabric configurations at large, wherein the switch computation unit provides for finding routes for such new requests by determining how to utilize unused switch bandwidth. The computational requirements of determining a small incremental change to a switch fabric are much less than having to re-compute the entire switch fabric configuration. Further, the

bookkeeping operations associated with the incremental changes are significantly less time-consuming to track than tracking the entire state of the switch fabric as it changes over time.

Electronic components are one of the limiting factors in designing switching systems operating at very high switching rates. Optical components are independent of the bit rate of the information carried by the optical signal they operate upon. Thus, optical switch fabrics, optical filters, and waveguide grating routers enable the design of very high capacity switching systems. The state of the art components of the above listed types is changing from being static, i.e., their configuration can be changed on a long time scale, to dynamic wherein their configuration can be changed on a very short time scale.

Moreover, when designing dynamic optical switching, an unresolved issue is how to control of switch configuration. Due to the lack of flexible and simple optical storage capability, optical packet switching—which provides a way of controlling the switching configuration responsive to the control information contained in the packet header — is impractical. Switching of time frames responsive to the common time reference provide a solution to the control of dynamic reconfigurable optical components.

Fast tunable lasers are being implemented and are going to be commercially available in the near future. Switch designs based on tunable lasers and a method to control them responsive to the common time reference are disclosed in the present invention.

Some aspects of the present invention utilize an alignment feature within an input port for aligning incoming data units to a time frame boundary prior to entry to a switch fabric. In a possible embodiment the alignment feature is designed using electrical components, such as random access memory (RAM) and digital circuitry. In another embodiment the alignment feature is designed using optical components, such as optical delay lines.

The present invention also discloses switch designs based on wavelength conversion and a method to control the wavelength conversion responsive to the common time reference. Optical

components such as wavelength converters, tunable lasers, tunable receivers, tunable filters, passive star couplers, and passive waveguide grating routers are utilized in the disclosed designs.

Some of the disclosed embodiments are based exclusively on optical components (i.e., the disclosed systems are all-optical dynamic switching systems). The designs and methods disclosed in the present invention provide a unique path to a prompt deployment and utilization of such dynamic optical components.

These and other aspects and attributes of the present invention will be discussed with reference to the following drawings and accompanying specification.

BRIEF DESCRIPTION OF THE DRAWINGS:

FIG. 1A is an architecture of a switching system responsive to a common time reference (CTR) based on tunable lasers and comprising a switch controller, a plurality of WDM de-multiplexers, a plurality of alignment subsystems — one for each input channel —, a plurality of WDM multiplexers, and a plurality of optical interconnections;

FIG. 1B is a timing diagram of a switching operation that is responsive to the common time reference with two pipeline forwarding phases: (i) receiving & alignment and (ii) switching & transmitting;

FIG. 2A contains a timing diagram of a common time reference (CTR) that is aligned with the coordinated universal time (UTC) standard, as utilized by the present invention, wherein the CTR is divided into a plurality of contiguous periodic super cycles each comprised of 100 contiguous time cycles each comprised of 800 contiguous time frames;

FIG. 2B contains a timing diagram of a common time reference (CTR) that is aligned with the coordinated universal time (UTC) standard, as utilized by the present invention, wherein the CTR is divided into a plurality of contiguous periodic super cycles each comprised of 100 contiguous time cycles each comprised of 100 contiguous time frames;

FIG. 3 shows how time frames are forwarded in a synchronized or pipelined manner responsive to UTC/CTR;

FIG. 4 is a block diagram of an alignment subsystem responsive to the common time reference (CTR);

FIG. 5A is a block diagram of a time-driven tunable laser comprising a tunable laser scheduling controller for changing the laser wavelength responsive to the common time reference;

FIG. 5B is a timing diagram showing the wavelength generated by the time-driven tunable laser during subsequent time frames;

FIG. 5C shows an output port selected on the downstream switch as a consequence of the usage of a selected wavelength during a selected time frame;

FIG. 6A is an architecture of a switching system responsive to the common time reference (CTR) based on tunable lasers and comprising a switch controller, a plurality of WDM de-multiplexers, a plurality of optical alignment subsystems — one for each input line —, a plurality of WDM multiplexers, and a plurality of optical interconnections;

FIG. 6B is a timing diagram of a switching operation that is responsive to the common time reference with two pipeline forwarding phases: (i) receiving & alignment and (ii) switching & transmitting;

FIG. 7A shows a communications link, the transmitting port of the switching system connected to the transmitting end of the communications link, and the receiving port of the switching system connected to the receiving end of the communications link, wherein the architecture of both switching systems is based on tunable lasers;

FIG. 7B is a timing diagram showing, for each time frame, from which input of the upstream switching system in FIG. 7A data units carried over the communications channel corresponding to the green wavelength had been sent;

FIG. 7C is a timing diagram showing, for each time frame, from which input of the upstream switching system in FIG. 7A data units carried over the communications channel corresponding to the red wavelength had been sent;

FIG. 8A is an architecture of a switching system responsive to the common time reference (CTR) based on tunable lasers and comprising a switch controller, a plurality of WDM de-multiplexers, a plurality of optical alignment subsystems — one for each input link — a plurality of WDM multiplexers, and an all-optical cross connect;

FIG. 8B is a timing diagram of a switching operation that is responsive to the common time reference with two pipeline forwarding phases: (i) receiving & alignment and (ii) switching & transmitting;

FIG. 9 shows a communications system responsive to the common time reference wherein data units are associated to a specific time frame, wherein such data units are transmitted over a specific wavelength across a Wavelength Division Multiplexing (WDM) network (or lambda switching network) whose network nodes (called wavelength routers or lambda routers) possibly route different wavelengths towards different destinations;

FIG. 10A is a timing diagram showing the wavelength used by the transmitting system in FIG. 9 during each time frame;

FIG. 10B shows a destination or egress point of the lambda switched network in FIG. 9 reached as a consequence of using a selected wavelength — as shown in FIG. 10A — during the corresponding time frame;

FIG. 10C is a timing diagram showing the wavelength used by the receiving system in FIG. 9 during each time frame;

FIG. 10D shows the source or ingress point of the lambda switched network in FIG. 9 from which data units are received as a consequence of using a selected wavelength — as shown in FIG. 10C — during the corresponding time frame;

FIG. 11A is an architecture of a switching system responsive to the common time reference (CTR) based on tunable lasers, a star coupler, and optical filters, and comprising a switch controller, a plurality of WDM de-multiplexers, a plurality of alignment subsystems — one for each input channel — and a plurality of WDM multiplexers;

FIG. 11B is a timing diagram of a switching operation that is responsive to the common time reference with two pipeline forwarding phases: (i) receiving & alignment and (ii) switching & transmitting;

FIG. 12 is a block diagram of an optical alignment subsystem based on an optical programmable delay system;

FIG. 13A is an architecture of a switching system responsive to the common time reference (CTR) based on tunable lasers (TL), a plurality of star couplers, optical multiplexers (MUXes), optical filters, alignment subsystems — one for each input channel — and comprising a switch controller, a plurality of WDM de-multiplexers (DMUXes), and a plurality of WDM multiplexers (MUXes);

FIG. 13B is a timing diagram of a switching operation that is responsive to the common time reference with two pipeline forwarding phases: (i) receiving & alignment and (ii) switching & transmitting;

FIG. 14 is an architecture of a switching system responsive to the common time reference (CTR) based on wavelength conversion (WLC) subsystems and comprising a switch controller, a plurality of optical alignment subsystems — one for each input line —, a plurality of star couplers, a plurality of wavelength division multiplexers (WDMs), and an optical interconnection subsystem between WLC subsystems and WDMs;

FIG. 15A is the block diagram of a wavelength conversion subsystem comprising a wavelength conversion (WLC) scheduling controller for changing the converted wavelength and

possibly the emitted wavelength responsive to the common time reference and to a wavelength mapping table;

FIG. 15B is a timing diagram showing the wavelength received by the wavelength conversion subsystem during subsequent time frames;

FIG. 16A is a block diagram of a possible embodiment of tunable wavelength conversion subsystem comprising a tunable receiver (TR) responsive to a color control signal and a fixed laser;

FIG. 16B is a timing diagram showing the wavelength received by the tunable receiver (TR) during subsequent time frames;

FIG. 16C shows a input port selected in the upstream switch as a consequence of the reception of a selected wavelength during a selected time frame;

FIG. 17A is a block diagram of a possible embodiment of tunable wavelength conversion subsystem comprising a tunable wavelength converter (TWLC) responsive to a color control signal;

FIG. 17B is a timing diagram showing the wavelength converted by the tunable wavelength converter (TWLC) during subsequent time frames;

FIG. 18A is a block diagram of a possible embodiment of tunable wavelength conversion subsystem comprising a tunable receiver (TR) and a tunable laser (TL) both responsive to a color control signal;

FIG. 18B is a timing diagram showing the wavelength received by the tunable receiver (TR) and the wavelength generated by the tunable laser (TL) during subsequent time frames;

FIG. 18C is a block diagram of a possible embodiment of tunable wavelength conversion subsystem comprising a tunable receiver (TR) responsive to a color control signal, an alignment subsystem responsive to the common time reference (CTR), and a fixed laser;

FIG. 19A depicts a possible embodiment of optical interconnection subsystem comprising a plurality of optical data lines between each input and a respective one of the outputs;

FIG. 19B depicts a possible embodiment of optical interconnection subsystem consisting in an optical cross connect (OXC) with a bi-directional control signal to control the connections between inputs and outputs of the OXC;

FIG. 20 is a block diagram of a possible embodiment of optical interconnection subsystem comprising a plurality of star couplers, a plurality of wavelength division multiplexers (WDMs), a plurality of filters, and a plurality of optical data lines between each star coupler and all of the WDMs;

FIG. 21 is an architecture of a switching system responsive to the common time reference (CTR) based on a waveguide grating router (WGR) and comprising a switch controller, a plurality of multiple wavelength conversion (WLC) subsystems and a plurality of optical alignment subsystems — one for each input line;

FIG. 22A is a block diagram of a multiple wavelength conversion subsystem comprising a multiple wavelength conversion (MWLC) scheduling controller for changing the set of converted wavelengths and the set of emitted wavelengths responsive to the common time reference and to a multiple wavelength mapping table;

FIG. 22B is a timing diagram showing the wavelengths conversions performed by the multiple wavelength conversion subsystem during subsequent time frames;

FIG. 23A is a block diagram of a possible embodiment of tunable multiple wavelength conversion subsystem comprising a tunable multiple wavelength converter responsive to a color control signal;

FIG. 23B is the block diagram of a possible embodiment of tunable multiple wavelength conversion subsystem comprising a wavelength division de-multiplexer (WDD), a plurality of tunable wavelength conversion subsystems, and a wavelength division multiplexer (WDM);

FIG. 24A exemplifies an operation of a WDM De-multiplexer (WDD);

FIG. 24B exemplifies an operation of a WDM Multiplexer (WDM);

FIG. 24C exemplifies an operation of a star coupler;

FIG. 25A exemplifies an operation of an optical crossconnect (OXC);

FIG. 25B exemplifies an operation of a waveguide grating router (WGR);

FIG. 25C exemplifies an operation of an optical filter;

FIG. 26A is a block diagram of a possible embodiment of tunable multiple wavelength conversion subsystem comprising a star coupler, a plurality of tunable wavelength conversion subsystems, and a WDM;

FIG. 26B is a timing diagram showing the wavelengths conversions performed by a tunable wavelength conversion subsystem during subsequent time frames;

FIG. 27 shows a possible embodiment of optical programmable delay system based on a programmable optical switching matrix and a set of fiber connections between switch outputs and switch inputs;

FIG. 28 shows a system in which two optical programmable delay systems are connected across a variable delay network, such as, SONET, ATM, IP, MPLS, all-optical with whole lambda switching, all-optical with fractional lambda switching;

FIG. 29 is a timing diagram of the alignment subsystem operation responsive to CTR and the serial link unique time reference (UTR);

FIG. 30 shows a possible configuration of an all-optical interface that dynamically adjusts the delay on an incoming optical signal with an optical programmable delay system.

FIG. 31 shows a possible embodiment of optical programmable delay system, according to the present invention, that is based on a programmable optical switching matrix, a plurality of wavelength division de-multiplexers (WDDs), a plurality of wavelength converters (WLCs) in both inputs and outputs, and a plurality of wavelength division multiplexers (WDMs), and comprises an programmable delay controller;

FIG. 32 shows a possible embodiment of optical programmable delay system, according to the present invention, that is based on a programmable optical switching matrix, a plurality of wavelength division de-multiplexers (WDDs), a plurality of multiple wavelength converters (MWLCs) only at the outputs, and a plurality of wavelength division multiplexers (WDMs), and comprises a programmable delay controller;

FIG. 33 is a pictorial representation of the alignment principle wherein unaligned time frames on all the inputs are aligned to the common time reference prior to being switched;

FIG. 34A shows a possible implementation of a serial optical delay line, with multiple tap points;

FIG. 34B shows a possible architecture of a fiber delay line realized as a parallel optical delay line, comprising a plurality of fibers of different length;

FIG. 35 shows a possible embodiment of optical programmable delay system, according to the present invention, that is based on an programmable optical wavelength switching matrix, a plurality of multiple wavelength converters (MWLCs) only at the outputs of the programmable optical wavelength switching matrix, and comprises a programmable delay controller.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT:

While this invention is susceptible of embodiment in many different forms, there is shown in the drawing, and will be described herein in detail, specific embodiments thereof with the understanding that the present disclosure is to be considered as an exemplification of the

principles of the invention and is not intended to limit the invention to the specific embodiments illustrated.

The present invention relates to a system and method for switching and forwarding data units over a network with optical WDM (wavelength division multiplexing) links. The switches of the network maintain a common time reference (CTR), which is obtained either from an external source (such as GPS -- Global Positioning System) or is generated and distributed internally. The common time reference is used to define time intervals, which include super cycles, time cycles, time frames, sub-time frames, and other kinds of time intervals. The time intervals are arranged both in simple periodicity and complex periodicity (like seconds and minutes of a clock).

A data unit that arrives to an input port of a switch or a grooming system or a de-grooming system, is switched to an output port based on either arrival time information and/or specific routing information in the data unit's header (e.g., IPv4 destination address in the Internet, VCI/VPI labels in ATM, MPLS–multi-protocol label switching–labels). Each switch along a route from a source to a destination forwards packets in periodic time intervals that are predefined using the common time reference.

A system is provided for managing data transfer of data units from a source to a destination. The transfer of the data units is provided during a predefined time interval, comprised of a plurality of predefined time frames. The system is further comprised of a plurality of switches. A common time reference signal is coupled to each of the switches, and a time assignment controller assigns selected predefined time frames for transfer into and out from each of the respective switches responsive to the common time reference signal.

Each communications channel may use a different time frame duration generated from the common time reference signal. Data units received during at least one of a plurality of time frames over at least one of a plurality of input channels can be transmitted during a single time

frame over a single output channel. Data units received during a single time frame from an input link are transmitted during at least one of a plurality of time frames over at least one of a plurality of output links.

For each switch, there is a first predefined time frame and a first predefined (optical) channel within which a respective data unit is transferred into the respective switch, and a second predefined time frame and a second predefined (optical) channel within which the respective data unit is forwarded out of the respective switch, wherein the first and second predefined time frames may have different durations. The time assignment provides consistent fixed time intervals between the input to and output from the fractional lambda pipe.

In a preferred embodiment, there is a predefined subset of the predefined time frames during which the data units are transferred in the switch, and for each of the respective switches, there are a predefined subset of the predefined time frames during which the data units are transferred out of the switch.

For each of the data units, there is an associated time of arrival to a respective one of the input ports. The time of arrival is associated with a particular one of the predefined time frames. For each of the mappings by the routing controller, there is an associated mapping by a scheduling controller, which maps each of the data units between the time of arrival and forwarding time out. The forwarding time out is associated with a specified predefined time frame.

There is a fixed time difference between the time frames for the associated time of arrival and forwarding time out for each of the data units. A predefined interval is comprised of a fixed number of contiguous time frames comprising a time cycle. Data units that are forwarded over a given fractional lambda pipe are forwarded from an output port within a predefined subset of time frames in each time cycle.

The time frames associated with a particular one of the switches within the fractional lambda pipe are associated with the same switch for all the time cycles, and are also associated with one of input into or output from the particular respective switch.

In one embodiment of the present invention, there is a constant fixed time between the input into and output from a respective one of the switches for each of the time frames within each of the time cycles. A fixed number of contiguous time cycles comprise a super cycle, which is periodic. Data units that are forwarded over a given fractional lambda pipe are forwarded from an output port within a predefined subset of time frames in each super cycle. Furthermore, the number of data units that can be forwarded in each of the predefined subset of time frames within a super cycle for a given fractional lambda pipe is also predefined.

In the preferred embodiment, the common time reference signal is devised from the GPS (Global Positioning System), and is in accordance with the UTC (Coordinated Universal Time) standard. The UTC time signal does not have to be received directly from GPS. Such signal can be received by using various means, as long as the delay or time uncertainty associated with that UTC time signal does not exceed half a time frame.

In one embodiment, the super cycle duration is equal to one second as measured using the UTC (Coordinated Universal Time) standard. In an alternate embodiment the super cycle duration spans multiple UTC seconds. In another alternate embodiment the super cycle duration is a fraction of a UTC second. In a preferred embodiment, the super cycle duration is a small integer number of UTC seconds.

Data units can be Internet Protocol (IP) data packets, multi-protocol label switching (MPLS) data packets, Point-to-Point Protocol (PPP) frames, High-level Data Link Control (HDLC) frames, Frame Relay frames, fiber channel data units, asynchronous transfer mode (ATM) cells, or SONET/SDH frames.

In accordance with one aspect of the present invention, a system is provided for transferring data units across a data network while maintaining for reserved data traffic constant bounded jitter (or delay uncertainty) and no congestion-induced loss of data units. Such properties are essential for many multimedia applications, such as, telephony and video teleconferencing.

FIG. 2 is an illustration of a common time reference (CTR) that is aligned to UTC. Consecutive time frames are grouped into time cycles. FIG. 2A and FIG. 2B provide examples of the common time reference (CTR) organized according to time frames of two different durations. As shown in the example illustrated in FIG. 2A, there are 800 time frames in each time cycle, each time frame lasting 12.5 microseconds. For illustration purposes, the time frames within a time cycle are numbered 1 through 800. According to the example shown in FIG. 2B, there are 100 time frames in each time cycle, each time frame lasting 125 microseconds. For illustration purposes, the time frames within a time cycle are numbered 1 through 100.

Time frames having different duration can be used for transmission over channels with different capacity. FIG. 2A provides an example in which 15.325 microseconds time frames are coupled to OC-192 (2.4 Gb/s) channels, while FIG. 2B exemplifies the coupling of 125 microseconds time frames with OC-3 (155 Mb/s) channels. In FIG. 2 the ratio **c** between the transmission speed of a high capacity channel and the transmission speed of a low capacity channel is defined. In the example in FIG. 2, **c** is 64.

As shown in FIG. 2, consecutive time cycles are grouped together into super cycles and in the two embodiments presented in FIG. 2A and FIG. 2B, respectively, there are 100 time cycles in each super cycle. For illustration purposes, time cycles within a super cycle are numbered 0 through 99. Super cycles 0 and m are shown in FIG. 2. Time cycles of different duration can be coupled to channels that deploy time frames of different duration. Equivalently,

super cycles comprised of a different number of time cycles can be coupled to different channels that deploy time frames having different duration.

FIG. 2 is illustrative of the relationship of time frames, time cycles, and super cycles; in alternate embodiments, the number of time frames within a time cycle may be different than 100 or 800, and the number of time cycles within a super cycle may be different than 100.

FIG. 2 illustrates how the common time reference signal can be aligned with the UTC (Coordinated Universal Time) standard. In this illustrated example, the duration of every super cycle is exactly one second as measured by the UTC standard. Moreover, as shown in FIG. 2, the beginning of each super cycle coincides with the beginning of a UTC second. Consequently, when leap seconds are inserted or deleted for UTC corrections (due to changes in the earth rotation period), the cycle and super cycle periodic scheduling will not be affected. The time frames, time cycles, and super cycles are associated in the same manner with all respective switches within the virtual pipe at all times.

In the embodiment illustrated in FIG. 2, the super cycle duration is equal to one second as measured using the UTC (Coordinated Universal Time) standard. In an alternate embodiment the super cycle duration spans multiple UTC seconds. In another alternate embodiment the super cycle duration is a fraction of a UTC second. In another embodiment, the super cycle duration is a small integer number of UTC seconds. A time frame may be further divided into time slots in the preferred embodiment, not illustrated in FIG. 2.

The Pipeline Forwarding (PF) Principle

In the method shown in FIG. 3, the content of the whole time frame is switched in the same way – namely, all the data packets in the time frame are switched to the same output port. Consequently, there is no need to use time slots. FIG. 3 shows an example of time frame (TF) switching and forwarding through a sequence of the switches: Switch **A**, Switch **B**, and Switch C. According to this specific example, the content of a TF that was forwarded from Switch **A** at

time frame 2 will reach Switch **B** at time frame 5, then switched to the output port at time 6, then forwarded at time frame 7 and will reach Switch **C** at time frame 9. The method of time frame switching is extremely useful in reducing the switching complexity of communications systems with a very high transmission rate (e.g., OC-48, OC-192, OC-768) and/or a plurality of wavelengths (i.e., WDM channels).

Time Driven Tunable Laser-Based Switching with Common Time Reference

Fractional lambda switching (FLSw) is based on two elements: (1) a Common Time Reference (CTR) throughout the network that is used to realize (2) Pipeline Forwarding (PF) of time frames (logical containers of data units) across multiple fractional lambda switches. FLSw is used for constructing a Fractional lambda pipe (FLP) that is equivalent to a leased line in circuit switching. Each FLP transports data packets of one protocol — such as, IP, MPLS, ATM, FR, FC, and SONET frames — thereby realizing the desired protocol independent property of optical switching.

The CTR is a reference clock, globally aligned with the Coordinated Universal Time (UTC), derived, for example, from the Global Positioning System (GPS) that is globally available at a minimal cost for accuracy of 1 microsecond. UTC can be as well derived from the GLONASS system and in the future it will be made available by the Galileo system. The CTR is partitioned into time frames, as shown in FIG. 2A, the duration of a time frame being an optical channel parameter. As shown in FIG. 2A, contiguous time frames are grouped into time cycles and contiguous time cycles are grouped into contiguous super cycles, wherein one super cycle is equal to and temporally aligned with one UTC second.

Pipeline forwarding (PF) of time frames for an FLP through a sequence of optical switches is realized by pre-scheduling the switching and forwarding of data units contained in each time frame through the switches. Thus, no control processing is necessary once data units within each time frame enter a FLP: all data units reaching a switch during one time frame are

automatically switched to the proper outgoing optical channel and then forwarded to the next switch on the route of the FLP, as exemplified in FIG. 3. Each FLP's switching schedule repeats itself every time cycle.

Advances in components for optical networking feature dynamic optical switch fabrics — e.g., based among others on electro-mechanical micro mirrors, holographic techniques, bubbles — and tunable lasers. The time required for changing the input/output configuration of dynamic optical switch fabrics is currently larger than the time required for changing the wavelength generated by a tunable laser. As a consequence, optical switch architectures based on tunable lasers rather than optical switch fabrics are appealing. The present disclosure describes a number of optical switch architectures based on tunable lasers.

FIG. 1A , FIG. 6A , FIG. 8A , FIG. 11A , and FIG. 13A show three possible architectures of a fractional lambda switch implemented using an array of tunable lasers **10200** and comprising a switch controller **13030.** In FIG. 1A , FIG. 6A , FIG. 8A , FIG. 11A , and FIG. 13A there are 16 input and output ports, each terminating a Wavelength Division Multiplexing (WDM) optical fiber **10010** carrying 16 wavelengths. In each of the architectures, an optical de-multiplexer (WDM DMUX) **10040** separates the 16 wavelengths. The WDM DMUX **10040** is coupled with an alignment subsystem **10100** or **10900**, as show in FIG. 1A , FIG. 6A , FIG. 8A , FIG. 11A , and FIG. 13A.

In an alternative embodiment subcarrier multiplexing (SCM) is used to provide for multiple channels on each fiber. SCM multiplexers and SCM de-multiplexers – instead of WDM multiplexers (MUXes) **10050** WDM de-multiplexers (DMUXes) **10040** - combine and separates the various optical channels on the fibers.

The switch performs PF that is realized in two operational phases, as shown in FIG. 1B. Data units belonging to a whole time frame received from each of the optical channels during Phase 1 are switched through the switch in Phase 2. In a possible embodiment, if Phase 1 begins

in time frame t, Phase 2 takes place in time frame t+1. In another embodiment, if Phase 1 ends in time frame t, Phase 2 takes place in time frame t+1. The 2 phase operation ensures that data units received from the various optical channels are aligned with the CTR before being switched. Phase 2 can be performed during either the time frame immediately following Phase 1, during time frame t+1 — immediate forwarding operation, or at a later time frame — non-immediate forwarding operation.

As shown in FIG. 1A , FIG. 6A , FIG. 8A , FIG. 11A , and FIG. 13A, during each time frame, aligned data units retrieved from the alignment subsystem are transmitted by a tunable laser **10200** to an output port where a WDM multiplexer (WDM MUX) **10050** combines the wavelength generated by the tunable laser with other 15 wavelengths onto the corresponding output fiber. As shown by the block diagram of a time driven tunable laser **10200** depicted in FIG. 5A , the control of the tunable laser is based on a wavelength-mapping table **10210** that is downloaded into each tunable laser scheduling controller **10220** by the switch controller **13030**. The wavelength-mapping table **10210** indicates to the tunable laser scheduling controller **10220** the wavelength to be used during each time frame of the time cycle or super cycle. As shown in FIG. 5B the tunable laser **10230** can change wavelength every time frame. The wavelength mapping follows a predefined pattern that repeats itself every time cycle or every super cycle.

The switch controller **13030** centrally computes the wavelength mapping table **10210** for all the tunable lasers **10200** guaranteeing that the same wavelength is not used during the same time frame by more than one tunable laser **10200** that is connected to the same output port WDM MUX **10050**, as shown in FIG. 1A , FIG. 6A , FIG. 8A , FIG. 11A , and FIG. 13A. The wavelength-mapping table **10210**, shown in FIG. 5, of a tunable laser **10200** is changed at the FLP control level, i.e., each time an FLP is set up or torn down.

Alignment is needed since the propagation delay on the communications channels between switches is not an integer multiple of time frames. Phase 1, shown in FIG. 1B, ensures

that data units received from the various optical channels are optically aligned with the CTR before being forwarded by the tunable laser **10200**.

<u>**Definition of Alignment:**</u> aligning the beginning and end of each time frame on each optical channel with the beginning and end of the CTR time frames.

The alignment principle is exemplified in FIG. 33. Time frames received on the input links **4130** are not aligned with the CTR. Each time frame contains a payload **4140**; an idle time acts as a safety margin separating the payloads **4140** of adjacent time frames. The payloads **4140u** of the time frames on the input links **4130** are not aligned with the CTR. Time frame payloads received from different input links **4130** are not necessarily aligned among themselves (see for example **4140u-1** and **4140u-N** in FIG. 33).

An alignment subsystem **4120** coupled with each input link **4130** delays incoming, unaligned time frame payloads **4140u** such that time frame payloads **4140a** are aligned upon exiting the alignment subsystem **4120**. Time frame payloads **4140a** on all the inputs **4125** of the switch fabric **50** are aligned to the CTR. Time frame payloads **4140** switched to all the outputs **4135** are aligned to the CTR.

FIG. 1A and FIG. 11A show per-wavelength alignment subsystems **10100** connected at the output of the WDM DMUXes **10040** and before the tunable lasers **10200**. While FIG. 6A and FIG. 8A show an optical alignment subsystem **10900**, which performs alignment on all the wavelengths carried by an optical fiber. Both alignment configurations — in FIG. 1A and FIG. 11A , and in FIG. 6A and FIG. 8A , respectively — take part in Phase 1 of PF, as shown in FIG. 1B, FIG. 11B, FIG. 6B, and FIG. 8B. Each of the per-wavelength alignment subsystems **10100** in FIG. 1A and FIG. 11A is implemented as a circular buffer of queues, each capable of storing one time frame worth of data, as shown in FIG. 4. During each time frame data units are stored in one queue **1550** and retrieved form another one **1550**; the writing and reading queues are

changed at the end of each time frame according to a pre-defined pattern that repeats itself every time cycle or every super cycle.

The optical alignment subsystem **10900** in FIG. 6A and FIG. 8A is based on a programmable delay system **10930**, as shown in FIG. 12 , guaranteeing that the overall delay experienced through the optical fiber and the programmable delay system **10930** is an integer number of time frames. As a result, when data units that have left the switch at the transmitting end of the fiber aligned with the CTR arrive at the WDM DMUX **10040** (see for example FIG. 6A) at the receiving end are still aligned with respect to then CTR. As shown in FIG. 12, the optical alignment subsystem **10900** comprises a delay controller **10990** comprised of a delineation controller **10920** that detects the time frame delimiters and an optical alignment controller **10910** that adjusts the delay introduced by the optical programmable delay system **10930** (note that the delay is modified only when the optical link propagation delay changes).

In the switch depicted in FIG. 1A and FIG. 6A the tunable lasers **10200** are statically connected to the same input WDM DMUX **10040** and the same output WDM MUX **10050**. Each WDM DMUX **10040** is coupled with tunable lasers **10200** connected to each one of WDM MUXes **10050**. Due to this interconnection configuration, the wavelength on which data units are carried on the input fiber determines their routing within the switch. Thus, the wavelength deployed by a tunable laser **10200** during a time frame determines the route the data units belonging to the time frame will take in the downstream switch on the path to their destination.

This WDM wavelength switching method (by using tunable lasers) is equivalent to label switching in ATM and MPLS. The label chosen in a switch determines the routing of a cell or MPLS packet in the next switch. Equivalently, the wavelength chosen in a switch determines the routing of a time frame worth of data in the following switch. Therefore, the wavelength entry in the tunable laser's wavelength mapping table **10210** (shown in FIG. 5) is equivalent to the **Next Hop Label Forwarding Entry** (NHLFE) of an MPLS switch.

The switch architecture presented in FIG. 1A and FIG. 6A is inexpensive and scalable because it is based on simple components and static interconnections among them. The control complexity is very low, since lasers are tuned no more than once every time frame. However, the resulting switch is not flexible, since only one wavelength from an input **10010** (WDM DMUX **10040**) can be switched to a given output **10020** (WDM MUX **10050**). A more flexible architecture can be obtained in two ways:

1. When the number of wavelengths per port is larger than the number of ports, and

2. When the switch architecture depicted in FIG. 1A and FIG. 6A is generalized, as depicted in FIG. 8A, which adds configurable connections between the tunable lasers **10200** and the outputs **10020** by means of an optical cross connect **10510**. The number of wavelengths on an input **10010** switched to a given output **10020** during the same time frame can be changed dynamically — even though on a possibly long time scale — to accommodate uneven traffic patterns.

__Detailed description of switch architectures__

FIG. 1A is the architecture of a possible embodiment of a time driven switch based on tunable lasers **10200**. The switching system **10000** presented in FIG. 1A has a plurality of inputs **10010** and outputs **10020**, each one consisting of an optical link with a plurality of wavelengths. The switching system **10000** in FIG. 1A comprises a switch controller **13030,** a plurality of WDM (wavelength division multiplexing) de-multiplexers (DMUX) **10040**, alignment subsystems **10100**, tunable lasers **10200**, and WDM multiplexers (MUXes) **10050,** and connection lines **10030** between each one of the tunable lasers **10200** and a respective one of the WDM multiplexers **10050**.

FIG. 24A shows the operation of a WDM DMUX (WDD) **10040** receiving an optical signal comprising a plurality of wavelengths, i.e., colors (green, red, and yellow in the example in FIG. 24A), on its optical input **14010**. The WDD **10040** separates the optical signal coupled to

each of the wavelengths onto a different output **14015.** In the example in FIG. 24A, the green wavelength is emitted on the top output **14015,** the red wavelength on the middle output **14015,** and the yellow wavelength on the lower output **14015.**

In the switch architecture shown in FIG. 1A, each WDM MUX **10040** separates each of the wavelengths received from the corresponding input **10010** and directs it to a corresponding alignment subsystem **10100.** A respective one of the plurality of alignment subsystems **10100** is associated to each respective one of the wavelengths received from each input **10010.** In the configuration shown in FIG. 1A the switching system **10000** comprises 16 inputs **10010** and outputs **10020,** each one comprising 16 wavelengths. Consequently, each WDM DMUX **10040** has 16 output lines and each WDM MUX **10050** has 16 input lines. For example, WDM DMUX *i* has 16 output lines **(*i*,1)** through **(*i*,16)** and WDM MUX *j* has 16 input lines **(*j*,1)** through **(*j*,16).**

The Alignment Subsystem **10100** aligns to the common time reference (CTR) data units received from its respective wavelength de-multiplexed by the respective WDM DMUX **10040** from the corresponding input **10010.** During each time frame, the tunable laser **10200** retrieves from its respective alignment subsystem **10100** data units to be switched during the current time frame and transmits them on a pre-selected wavelength on the connection line **10030** with its respective one of the WDM MUXes **10050.**

Each WDM MUX **10050** multiplexes the wavelengths received on its respective input lines **10030** from the tunable lasers **10200** and transmits them on its respective output **10020.** For example, WDM MUX *j* **10050** multiplexes on output *j* **10020** the wavelengths received on the connection lines **10030 (*j*,1)** through **(*j*,16).**

Each tunable laser **100200** can change the wavelength on which it transmits during each time frame according to the information stored in a (sub)-time frame table **10210** downloaded in the tunable laser controller **10220** (see FIG. 5) by the switch controller **13030.** By properly building the (sub)-time frame tables **10210** for all the tunable lasers **10200,** the switch controller

13030 ensures that no more than one tunable laser **10200**, among the plurality of tunable lasers **10200** connected to the same WDM MUX **10050**, transmits over the same wavelength during the same time frame.

The switch controller **13030** is responsible for changing, responsive to the CTR, the configurations of the WDM DMUX **10040**, alignment subsystem **10100**, tunable laser **10200**, and WDM MUX **10050**, in FIG. 1A, responsive to the CTR and Unique Time Reference (UTR). The UTR is described in more details in the specifications of FIG. 7 and FIG. 29. The WDM DMUXes **10040**, alignment subsystems **10100**, tunable lasers **10200**, and WDM MUXes **10050**, are controlled by the switch controller **13030** through four bi-directional control lines **13031, 13032, 13033**, and **13034**, respectively. Each of the four control lines provides configuration information from the switch controller **13030** to the WDM DMUXes **10040**, alignment subsystems **10100**, tunable lasers **10200**, and WDM MUXes **10050**, respectively; and via the four bi-directional control lines **13031, 13032, 13033**, and **13034**, the switch controller **13030** receives various status and control information from the WDM DMUXes **10040**, alignment subsystems **10100**, tunable lasers **10200**, and WDM MUXes **10050**, respectively. In a possible embodiment the switch controller **13030** receives the UTR corresponding to an input channel through the bidirectional control signal **13032** from the corresponding alignment subsystem **10100**.

With reference to FIG. 1A, the topology of the interconnection lines **10030** between each of the tunable lasers **10200** and a respective one of the WDM MUXes **10050**, determines the route of the data units received on each wavelength from each input **10010**. For example, data units received on a first selected wavelength of input 1 **10010** which is de-multiplexed by the WDM DMUX **10040** on its output line 1 **(1,1)** are going to be transmitted by the respective first tunable laser **10200** on output 1 **10020**. This is a consequence of the fact that the respective first

tunable laser **10200** is connected via a first one of the connection lines **10030** to input line **(1,1)** of the WDM MUX 1 **10050** that is coupled to output 1 **10020**.

Instead, with reference to FIG. 1A, data units received on a second selected wavelength of input 1 **10010** which is de-multiplexed by the WDM DMUX **10040** on its output line *j* **(1,*j*)** are going to be transmitted by the respective second tunable laser **10200** on output *j* **10020**. This is a consequence of the fact that the respective second tunable laser **10200** is connected via a second one of the connection lines **10030** to input line **(*j*,1)** of the WDM MUX *j* **10050** that is coupled to output *j* **10020**.

In other words, the wavelength over which data units are carried on an input link **10010** determines the output **10020** on which those data units will be forwarded. The wavelength on which the data units are transmitted by the tunable laser **10200** coupled to the input **10010** and wavelength from which they are received determines the routing in the switching system **10000** coupled to the selected output **10020**.

FIG. 7A shows the interconnection between two tunable laser-based switching systems **10000**, wherein the output *j* of the upstream switching system **U** is coupled to the input *i* of the downstream switching system **D**. The WDM MUX *j* **10050** coupled to output *j* of switching system **U** combines all the wavelengths received through the interconnection lines **10030** from the respective ones of the plurality of tunable lasers (not shown in FIG. 7A) comprised in switching system **U**.

Each of the wavelengths multiplexed by WDM MUX *j* **10050** in switching system **U** is then de-multiplexed from input *i* by WDM DMUX *i* **10040** of switching system **D** on a respective one of the output lines **10410** **(*i*,1)** through **(*i*,16)**. The transported data units are aligned to the common time reference and then transmitted by a corresponding tunable laser **10200** over a corresponding connection line **10030** connected to a selected output (not shown in FIG. 7A) of switching system **D**.

In other words, the wavelength on which data units are transmitted on their respective connection line **10030** within the switching system **U** determines the WDM DMUX's output line **10410** on which the data units will be transferred to their respective alignment subsystem **10100** and tunable laser **10200** within switching system **D** and, ultimately, the switching system **D**'s output the data units will reach.

Thus, data units carried by each wavelength on the interconnection optical link **10420** between the switching system **U** and the switching system **D** are switched by switching system **D** to a pre-defined output. Data units transmitted on a first selected wavelength of the interconnection optical link **10420** are transmitted by a selected one of the switching system **U**'s tunable lasers on a corresponding connection line **10030.** In other words, data units transmitted on a first selected wavelength of the interconnection optical link **10420** transit through a selected one of the switching system **U**'s DWM MUX *j* **10050 (*j*,1)** through **(*j*,16).** The switch architecture depicted in FIG. 1A shows that data units flowing through each of the WDM MUX **10050** inputs **10030** had previously received by a selected respective one of the switching system's **10000** inputs **10010.** For example, data units flowing through input line **10030 (*j*,1)** had previously been received on one of the wavelengths of input 1 **10010.**

Since the tunable lasers **10200** can change the wavelength on which they transmit for each time frame, during each time frame data units transmitted on a first selected wavelength of the interconnection optical link **10420** transit through a selected one of the switching system **U**'s DWM MUX *j* **10050 (*j*,1)** through **(*j*,16).**

FIG. 7B shows a timing diagram describing the origin of data units carried by the green wavelength of the optical link **10420** between switching system **U** and switching system **D.** The timing diagram shows the time frames **TF** of the UTR (Unique Time Reference) coupled to the optical link **10420.** Data units received on each one of the time frames where switched to the output *j* of switching system **U** after having been received on a selected one of the inputs of

switching system **U**. The mapping of the receiving input into output *j* during each specific time frame is pre-defined and repeats itself every time cycle or super cycle.

FIG. 7C shows a timing diagram describing the origin of data units carried by the red wavelength on the optical link **10420** between switching system **U** and switching system **D**. The timing diagram shows the time frames **TF** of the UTR (Unique Time Reference, see below specification of FIG. 4) coupled to the optical link **10420**. Data units received on each one of the time frames where switched to the output *j* of switching system **U** after having been received on a selected one of the inputs of switching system **U**. The mapping of the receiving input onto output *j* during each specific time frame is pre-defined and repeats every time cycle or super cycle.

As shown by the timing diagrams in FIG. 7B and FIG. 7C, with the switch architecture depicted in FIG. 1A, data units carried over different wavelengths during the same time frame on the link **10420** between switching system **U** and switching system **D** had been received by switching system **U** from different inputs **10010**. In alternative embodiments, data units received by switching system **U** from the same input **10010** on a plurality of wavelengths are transmitted on a plurality of wavelengths of the same output **10020** during the same time frame. One possible such embodiment is realized through a different configuration of the interconnection lines **10030** within the switching system **10000** depicted in FIG. 1A. A possible implementation realizes the interconnection lines **10030** through a programmable cross connect **10510** so that the configuration of the interconnections between tunable lasers **10200** and WDM MUXes **10050** — i.e., outputs **10020** — can be changed during the operation of the switching system (see FIG. 8A). Another possible implementation features a number of wavelengths on each input **10010** larger than the number of inputs **10010**. This configuration allows data units form a plurality of wavelengths of the same input **10010** to be switched to and forwarded from the same output **10020** during the same time frame, wherein data units received on different wavelengths are

transmitted on the output **10020** over different wavelengths. The programmable cross connect **10510** can be implemented in either electronic technology or optical technology.

FIG. 4 depicts the block diagram of a possible embodiment of an alignment subsystem **10100** comprising an alignment scheduling controller **10110** responsive to the common time reference (CTR) **002**, a 1-to-k selector **10150** responsive to the Select-in signal **10120**, a plurality of (sub)-time frame queues **1550**, and a k-to-1 selector **10140** responsive to the Select-out signal **10130**.

The alignment subsystem **10100** aligns data units received over the corresponding wavelength *j* of the corresponding input *i* **10010** to the CTR. With reference to FIG. 1, data units received from wavelength *j* of the corresponding input *i* **10010** are transferred form the WDM DMUX **10040** coupled to input *i* to the corresponding one of the alignment subsystems **10100** coupled to wavelength *j* through data line **10160 (*i,j*)**.

The wavelengths of a single optical link connected to an input **10010** of the switching system **10000** in FIG. 1 has a unique time reference (UTR-i), as shown in FIG. 29, that is independent of the CTR **002**, also shown in FIG. 29. In the example in FIG. 4, the TF duration deployed on wavelength *j* of input *i* is **TFi_j**. Time frames of the common time reference and the UTR-i are possibly divided in sub-time frames of duration **subTF**.

Between successive super cycles, time cycles, TFs and sub-time frames (subTFs) of the UTR-i there can be explicit or implicit delimiters. Explicit delimiters can be realized by one of a plurality of different methods. There can be a different delimiter control word to signal the beginning of a new TF (i.e., a time frame delimiter – TFD), time cycle (i.e., a time cycle delimiter – TCD) and super cycle (i.e., a super cycle delimiter – SCD). The delimiter control word can be included in the stream of bits or symbols transmitted at the physical level, e.g., with an 8B/10B encoding. The explicit delimiter signaling can be realized by the SONET/SDH path overhead field that was designed to carry control, signaling and management information.

Alternatively, the explicit delimiter signaling can be embedded in the PPP, HDLC, IP header, or in any protocol header exchanged over the communications links between switches. An implicit delimiter can be realized by measuring the UTR-i time with respect to the CTR. An alternative way of implementing an implicit delimiter is by counting the number of bytes from an explicit delimiter.

By using the above mentioned delimiters, the alignment scheduling controller **10110** is capable of devising the UTR-i from the information received from input line **10160**.

A plurality of buffer queues **1550** are part of each alignment subsystem **10100**, wherein data units received on the input line **10160** are stored in a respective one of the buffer queues during each one of the UTR-i time frames. In an alternative embodiment, data units received on the input line **10160** are stored in a respective one of the buffer queues during each one of the UTR-i sub-time frames.

The alignment scheduling controller **10110** logically maps, for each of the (UTR-i) time frames or subTFs, the respective incoming wavelength coupled to the input line **10160** to selected buffer queues **1550**, and logically maps, for each of the CTR TFs or subTFs, selected ones of the plurality of buffer queues **1550** to the output line **10165**.

The Select-in signal **10120** generated by the alignment scheduling controller **10110** determines which of the buffers **1550** will receive data units from the input line **10160** at every time frame **TF*i_j*** or sub-time frame **subTF** as it is defined by the (UTR-i). The selection by the 1-to-k selector **10150** is responsive to the Select-in signal **10120** received from the alignment scheduling controller **10110**. The buffer queues **1550** in the alignment subsystem **10100** for each time frame or sub-time frame can be filled with data units in arbitrary order to an arbitrary level, prior to output.

The alignment scheduling controller **10110** further provides for coupling of selected ones of the time frame or sub-time frame queues **1550** to the output line **10165**, for transfer of the

respective stored data units during the respective CTR time frames or sub-time frames. This operation is performed by the k-to-1 selector **10140** responsive to the Select-out signal **10130**, as shown in FIG. 4.

For each of the subTFs of the CTR, only one of the buffer queues **1550** is associated with the outgoing line **10165**. For each of the subTFs of the UTR-i, only one of the buffer queues is associated with the incoming line **10160**. In the preferred embodiment, the same buffer queue **1550** is never associated at the same time with both the incoming line **10160** and the outgoing line **10165**. In an alternative embodiment, a same queue **1550** can be associated to both the incoming line **10160** and the outgoing line **10165** at the same time.

According to the preferred embodiment, the alignment subsystem **10100** must have 3 TF queues **1550** in order to operate on a time frame basis — i.e., in order for the respective switching system **10000** to be capable of switching the content of entire time frames — according to the immediate forwarding principle. The alignment subsystem **10100** must have more than 3 TF queues **1550** in order to operate on a time frame basis — i.e., in order for the respective switching system **10000** to be capable of switching the content of entire time frames — according to the non-immediate forwarding method. In the non-immediate forwarding method a data unit is delayed in the alignment subsystem **10000** until there is an available time frame for it to be switched and to be transmitted on the selected one of the outgoing wavelengths of the selected one of the outputs **10020**. In this method, the delay is increased, i.e., more time frames may be needed to get from input **10160** to output **10165** of the alignment subsystem **10100**. The non-immediate forwarding method adds flexibility to the scheduling process of fractional lambda pipes.

The alignment subsystem **10100** must have 3·***TFi_j*/subTF** subTF queues **1550** in order to operate on a sub-time frame basis — i.e., in order for the respective switching system **10000** to be capable of switching the content of sub-time frames — according to the immediate

forwarding principle. The alignment subsystem **10100** must have more than 3·**TF*i_j*/subTF** subTF queues **1550** in order to operate on a sub-time frame basis — i.e., in order for the respective switching system **10000** to be capable of switching the content of sub-time frames — according to the non-immediate forwarding method. In the non-immediate forwarding method a data unit is delayed in the alignment subsystem **10000** until there is an available sub-time frame for it to be switched and to be transmitted on the selected one of the outgoing wavelengths of the selected one of the outputs **10020**. In this method, the delay is increased, i.e., more sub-time frames may be needed to get from input **10160** to output **10165** of the alignment subsystem **10100**.

The alignment scheduling controller **10110** generates the Select-in **10120** and the Select-out **10130** signals responsive to the content of a queue mapping table **10115** that is pre-computed and downloaded in the alignment scheduling controller **10110** by the switch controller **13030** through the control line **13032**. The queue mapping table **10115** contains:

(i) for each time frame or sub-time frame of the UTR-i the (sub)time frame queue **1550** in which data units arriving from the input line **10160** are to be stored;

(ii) for each time frame or sub-time frame of the CTR the (sub)time frame queue **1550** from which data units are to be retrieved for transmission on the output line **10165**.

In other words, the queue mapping table **10115** contains a mapping between each UTR-i time frame or sub-time frame and a selected one of the (sub)TF queues **1550** and between each CTR time frame or sub-time frame and a selected one of the (sub)TF queues **1550**. The above mentioned mappings are calculated and written in the queue mapping table **10115** of each one of the alignment scheduling controllers **10110** by the switch controller **13030**; the switch controller

13030 calculates time frame schedules on all the wavelengths of all the inputs **10010** and outputs **10020**.

In a possible embodiment, the above mentioned mapping repeats each time cycle or each super cycle.

An alternative embodiment features a centralized alignment scheduling controller that generates the Select-in **10120** and Select-out **10130** signals for all the alignment subsystems **10100** in the respective switching system **10000**. In such an embodiment the centralized alignment scheduling controller can be implemented within the switch controller **13030**.

FIG. 5A shows the block diagram of a possible implementation of a time driven tunable laser **10200** comprising a tunable laser (TL) scheduling controller **10220** responsive to the CTR **002** and a control signal **13033** from the switch controller, and a tunable laser transmitter **10230** responsive to a color control signal **10240**.

The tunable laser **10200** receives data units from its input line **10165** and a tunable laser transmitter **10230** transmits them on a selected wavelength over the output line **10030**. The selected wavelength used by the tunable laser transmitter **10230** is determined responsive to the color control signal **10240** generated by the TL scheduling controller **10220**.

In a possible embodiment the color control signal **10220** selects a different wavelength for transmission of data units by the tunable laser transmitter **10230** during each time frame. FIG. 5B is a sample timing diagram describing the operation of a tunable laser transmitter **10230** in this embodiment. The timing diagram shows a sequence of CTR time frames **TF**, and, for each time frame, the wavelength used for transmission by the tunable laser transmitter **10230**, wherein each wavelength is identified by the color (green, yellow, red, and blue) of the corresponding light beam.

FIG. 5C shows the implication of the choice of a selected wavelength on the routing of data units transmitted over the wavelength. Different wavelengths are routed to different outputs

10020 of the downstream switching system **10000** due to the interconnections between the output lines **10160** of the WDM DMUXes **10040** and the input lines **10030** of the WDM MUXes **10050** of each output **10020**, as shown in the switch architecture depicted in FIG. 1A. For example, in a possible configuration data units transmitted by the tunable laser **10200** on the green wavelength during a first selected time frame are going to be routed to and — during a second selected time frame, wherein the second time frame follows the first one — forwarded through output 1 of the next switching system **10000** traversed by the data units, i.e., the switching system **10000** connected to the output **10020** with to the output line **10030** of the tunable laser **10200** is coupled. Instead, data units transmitted by the tunable laser **10200** on the yellow wavelength during a third selected time frame are going to be routed to and — during a fourth selected time frame, wherein the fourth time frame follows the third one — forwarded through output 3 of the next switching system **10000** traversed by the data units, i.e., the switching system **10000** connected to the output **10020** to which the output line **10030** of the tunable laser **10200** is coupled.

In an alternative embodiment the color control signal **10220** selects a different wavelength for transmission of data units by the tunable laser transmitter **10230** during each sub-time frame.

The TL scheduling controller **10220** generates the color control signal **10240** responsive to both the CTR **002** and the content of a wavelength mapping table **10210**. The wavelength mapping table **10210** contains the mapping between each CTR time frame or sub-time frame and the wavelength to be used by the tunable laser transmitter **10230** for transmitting during the selected CTR time frame or sub-time frame.

The above mentioned mapping is calculated and written in the wavelength mapping table **10210** of each one of the TL scheduling controllers **10220** by the switch controller **13030**

through control signal **13033**. The switch controller **13030** calculates time frame or sub-time frame schedules on all the wavelengths of all the inputs **10010** and outputs **10020**.

In a possible embodiment, the above mentioned mapping repeats each time cycle or each super cycle.

An alternative embodiment features a centralized TL scheduling controller that generates the color control signal **10240** for all the tunable lasers **10200** in the respective switching system **10000**. In such an embodiment the centralized TL scheduling controller can be implemented within the switch controller **13030**.

FIG. 6A is the architecture of an alternative embodiment of a time driven switch based on tunable lasers **10200**. The switching system **10000** presented in FIG. 6A has a plurality of inputs **10010** and outputs **10020**, each one consisting of an optical link with a plurality of wavelengths. The switching system **10000** in FIG. 6A comprises a switch controller **13030** a plurality of optical alignment subsystems **10900**, WDM (wavelength division multiplexing) de-multiplexers (DMUX) **10040**, tunable lasers **10200**, and WDM multiplexers (MUXes) **10050**, and connection lines **10030** between each one of the tunable lasers **10200** and a respective one of the WDM multiplexers **10050**. The WDM DMUXes **10040**, optical alignment subsystems **10900**, tunable lasers **10200**, and WDM MUXes **10050**, are controlled by the switch controller **13030**, responsive to the CTR **002**, through four bi-directional control lines **13031, 13737, 13033,** and **13034**, respectively. Each of the four control lines provides configuration information from the switch controller **13030** to the WDM DMUXes **10040**, optical alignment subsystems **10900**, tunable lasers **10200**, and WDM MUXes **10050**; and via the four bi-directional control lines **13031, 13737, 13033,** and **13034**, the switch controller **13030** receives various status and control information from the WDM DMUXes **10040**, alignment subsystems **10100**, tunable lasers **10200**, and WDM MUXes **10050**.

A respective one of the plurality of the optical alignment subsystems **10900** is associated to each respective one of the inputs **10010**. The Optical Alignment Subsystem **10900** aligns to the common time reference (CTR) data units received over the plurality of wavelengths of its respective input **10010**.

Each WDM DMUX **10040** divides each of the wavelengths received from the corresponding optical input line **10320** and directs it to a corresponding tunable laser **10200**. In the configuration shown in FIG. 6A the switching system **10000** comprises 16 inputs **10010** and outputs **10020**, each one comprising 16 wavelengths. Consequently, each WDM DMUX **10040** has 16 output lines **10310** and each WDM MUX **10050** has 16 input lines **10030**. For example, WDM DMUX *i* has 16 output lines **(*i*,1)** through **(*i*,16)** and WDM MUX *j* has 16 input lines **(*j*,1)** through **(*j*,16)**.

The switch in FIG. 6A performs PF that is realized in two operational phases, as shown in FIG. 6B. Data units belonging to a whole time frame received from each of the optical channels during Phase 1 are switched through the switch in Phase 2. In a possible embodiment, if Phase 1 begins in time frame t, Phase 2 takes place in time frame t+1. In another embodiment, if Phase 1 ends in time frame t, Phase 2 takes place in time frame t+1. The 2 phase operation ensures that data units received from the various optical channels are aligned with the CTR before being switched. Phase 2 can be performed during either the time frame immediately following Phase 1, during time frame t+1 — immediate forwarding operation, or at a later time frame — non-immediate forwarding operation.

During each time frame, the tunable laser **10200** in FIG. 6A receives from its respective line **10310** data units to be switched during the current time frame and transmits them over a pre-selected wavelength on the connection line **10030** to its respective one of the WDM MUXes **10050**.

Each WDM MUX **10050** multiplexes the wavelengths received on its respective input lines **10030** from the tunable lasers **10200** and transmits them on its respective output **10020**. For example, WDM MUX *j* **10050** multiplexes on output *j* **10020** the wavelengths received on the connection lines **10030** **(*j*,1)** through **(*j*,16)**.

As shown in FIG. 5A, each tunable laser **10200** can change the wavelength on which it transmits for each time frame according to the information stored in a (sub)-time frame table **10210** downloaded in the tunable laser controller **10220** by the switch controller **13030** through control line **13033**. By properly building the (sub)-time frame tables **10210** for all the tunable lasers **10200** of the switch in FIG. 6A, the switch controller **13030** ensures that no more than one among the plurality of tunable lasers **10200** connected to the same WDM MUX **10050** transmits over the same wavelength during the same time frame.

The topology of the interconnections **10030** between each tunable laser **10200** and a respective one of the WDM MUXes **10050**, determines the route of the data units received on each wavelength from each input **10010**. For example, with reference to FIG. 6A, the data units received on a first selected wavelength of input 1 **10010** which is de-multiplexed by the WDM DMUX **10040** on its output line 1 **(1,1)** are going to be transmitted by the respective first tunable laser **10200** on output 1 **10020**. This is a consequence of the fact that the respective first tunable laser **10200** is connected via a first one of the connection lines **10030** to input line **(1,1)** of the WDM MUX 1 **10050** that is coupled to output 1 **10020**.

Instead, with reference to FIG. 6A, data units received on a second selected wavelength of input 1 **10010** which is de-multiplexed by the WDM DMUX **10040** on its output line *j* **(1,*j*)** are going to be transmitted by the respective second tunable laser **10200** on output *j* **10020**. This is a consequence of the fact that the respective second tunable laser **10200** is connected via a second one of the connection lines **10030** to input line **(*j*,1)** of the WDM MUX *j* **10050** that is coupled to output *j* **10020**.

In other words, the first wavelength over which data units are carried on a selected input link **10010** determines the selected output **10020** on which those data units will be forwarded. The second wavelength on which the data units are transmitted by the tunable laser **10200** coupled to the selected input **10010** and first wavelength from which they are received determines the routing in the switching system **10000** coupled to the selected output **10020**.

FIG. 12 shows the block diagram of an optical alignment subsystem **10900** deployed in the embodiment of a tunable laser-based time driven switch **10000** depicted in FIG. 6A. The optical alignment subsystem **10900** in FIG. 12 comprises a programmable delay system **10930** that delays the optical signal from the input **10010** responsive to the adjust delay control signal **10940**, a delay controller **10990** comprised of a delineation controller **10920** responsible to devise the unique time reference (UTR) associated to input **10010** and an optical alignment controller **10910** responsible for determining, responsive to the CTR **002** and the UTR-i **10950**, the delay needed to align to the CTR data units received from the input **10010**. The optical alignment controller **10910** exchanges control information (i.e., configuration and state information) with the switch controller **13030** through bi-directional control line **13737**.

Time frames on the input **10010** are aligned to the unique time reference (UTR) associated to the respective optical communication link i — UTR-i. The programmable delay system **10930** delays the optical signal received from the input **10010** in a way that time frames coupled to data units carried by the optical signal on the outgoing optical link **10320** are aligned to the common time reference (CTR). The programmable delay system **10930** can be realized, for example, through an optical delay line with multiple tap points (shown in FIG. 34A), or through a fiber delay line comprising a plurality of fibers of different length (shown in FIG. 34B), or according to one of the embodiments presented below in this disclosure (see FIG. 27, 31, and 32).

The amount of delay that the programmable delay system **10930** has to introduce depends on the phase difference between the CTR and UTR-i. This phase difference can change over time as a result of changes in the propagation delay over the communications link coupled to the input i **10010**. According to the architecture shown in FIG. 12, the optical alignment controller **10910** compares the UTR-i and the CTR to determine the proper delay that the programmable delay system **10930** should introduce. The optical alignment controller **10910** adjusts the delay introduced by the programmable delay system **10930** through the adjust delay control signal **10940**. The optical alignment controller **10910** receives the CTR signal **002** from an external device, such as, for example, a GPS receiver board, and the UTR-i through the UTR-i line **10950** from the delineation controller **10920**.

The delineation controller **10920** devises the UTR-i directly from the optical signal received through the input **10010**. One way for the delineation controller **10920** to devise the UTR-i is through implicit or explicit time frame delimiters embedded in the flow of data units. Explicit delimiters can be realized by one of a plurality of different methods. There can be a different delimiter control word to signal the beginning of a new TF (i.e., a time frame delimiter – TFD), time cycle (i.e., a time cycle delimiter – TCD) and super cycle (i.e., a super cycle delimiter – SCD). The explicit delimiter signaling can be realized by the SONET/SDH path overhead field that was design to carry control, signaling and management information. An implicit delimiter can be realized by measuring the UTR-i time with respect to the CTR. An alternative way of implementing an implicit delimiter is by counting the number of bytes from an explicit delimiter.

Alternatively, time frame delineation can be based on time frame delimiter in the optical signal carried on the communications link coupled to input i. A possible embodiment of time frame delimiter consists of dedicating one of the wavelengths of the communications link for transmission of the delimiter. The delineation controller **10920** detects the delimiters on the

dedicated wavelength and devises the UTR-i. In an alternative embodiment the time frame delimiter are realized by introducing a gap, i.e., a period of dark, in the optical signal on the boundary between two adjacent time frames, as shown in FIG. 33. In other words, for each time frame, after having transmitted all the data units belonging to the time frame, the laser transmitter of each wavelength is turned off before starting transmitting data units belonging to the next time frame, as shown by the example in FIG. 33. The delineation controller **10920** detects the gaps on at least one of the wavelengths of the input **10010** and uses the derived timing information to devise the link's UTR.

FIG. 30 shows a second possible embodiment of optical alignment subsystem **10900** based on an programmable delay system **10930** and comprising a delay controller **10990** further comprised of an optical alignment controller **10910** and a delineation controller **10920**. The programmable delay system **10930** delays the optical signal from the input **10010** responsive to the adjust delay control signal **10940**. The delineation controller **10920** responsible to devise the aligned unique time reference (aUTR-i) **10960** associated to outgoing optical link **10320** corresponding to input i **10010**. The optical alignment controller **10910** is responsible for determining, responsive to the CTR **002** and the aUTR-i **10960**, the delay needed to align to the CTR data units received from the input **10010**, i.e., to align the aUTR-i **10960** and the CTR **002**.

Time frames on the input **10010** are aligned to the unique time reference (UTR-i) associated to the respective optical communication link I — UTR-i. The programmable delay system **10930** delays the optical signal received from the input **10010** in a way that time frames associated to data units carried by the aligned output signal on the outgoing optical link **10320** constituting the aUTR-i, are aligned to the common time reference (CTR). The programmable delay system **10930** can be realized, for example, through an optical delay line with multiple tap points (a.k.a. serial optical delay line), or through a fiber delay line comprising a plurality of

fibers of different length (a.k.a. parallel optical delay line), or according to one of the embodiments presented below in this disclosure (see FIG. 27, 31, and 32).

The amount of delay that the programmable delay system **10930** has to introduce depends on the phase difference between the CTR and aUTR-i, i.e., ultimately the phase difference between CTR and UTR-i. This phase difference can change over time as a result of changes in the propagation delay over the communications link coupled to the input i **10010**. The optical alignment controller **10910** compares the aUTR-i and the CTR to determine the proper delay that the programmable delay system **10930** should introduce in order to keep the aUTR-i signal **10960** aligned to the CTR **002**. The optical alignment controller **10910** adjusts the delay introduced by the programmable delay system **10930** through the adjust delay control signal **10940**. The optical alignment controller **10910** receives the CTR signal **002** from an external device, such as, for example, a GPS receiver board, and the aUTR-i through the aUTR-i line **10960** from the delineation controller **10920**.

The delineation controller **10920** devises the aUTR-i directly from the aligned output signal transported by the outgoing optical link **10320**. One way for the delineation controller **10920** to devise the aUTR-i is through implicit or explicit time frame delimiters embedded in the flow of data units Explicit delimiters can be realized by one of a plurality of different methods. There can be a different delimiter control word to signal the beginning of a new TF (i.e., a time frame delimiter – TFD), time cycle (i.e., a time cycle delimiter – TCD) and super cycle (i.e., a super cycle delimiter – SCD). The explicit delimiter signaling can be realized by the SONET/SDH path overhead field that was design to carry control, signaling and management information. An implicit delimiter can be realized by measuring the UTR-i time with respect to the CTR. An alternative way of implementing an implicit delimiter is by counting the number of bytes from an explicit delimiter.

Alternatively, time frame delineation can be based on time frame delimiters in the optical signal carried on the communications link coupled to input i. A possible embodiment of time frame delimiter consists of dedicating one of the wavelengths of the communications link for transmission of the delimiter. The delineation controller **10920** detects the delimiters on the dedicated wavelength and devises the aUTR-i. In an alternative embodiment time frame delimiters are realized by introducing a gap, i.e., a period of dark, in the optical signal on the boundary between two adjacent time frames, as shown in FIG. 33. In other words, for each time frame, after having transmitted all the data units belonging to the time frame, the laser transmitter of each wavelength is turned off before starting transmitting data units belonging to the next time frame, as shown in FIG. 33. The delineation controller **10920** detects the gaps on at least one of the wavelengths of the outgoing optical link **10320** and uses the derived timing information to devise the aUTR-i corresponding to input link i **10010**.

FIG. 8A depicts the architecture of an alternative embodiment of a tunable laser-based time driven switch **10000** in which an optical cross connect **10510** is used for interconnecting the plurality of tunable lasers **10200** with their respective ones of the WDM MUXes **10050**.

The output **10520** of each tunable laser **10200** is coupled to an input line of the optical cross connect **10510**. The inputs **10530** of each WDM MUX are coupled to an output of the optical cross connect **10510**. The optical cross connect **10510** is implemented using optical switching technologies such as, but not limited to, micro electro-mechanical system (MEMS) mirrors, bubbles, holography. The optical cross connect **10510** is capable of changing the connections between the inputs **10520** and the outputs **10530** responsive to a control signal **13035** from the switch controller **13030**. The WDM DMUXes **10040**, optical alignment subsystems **10900**, tunable lasers **10200**, optical cross connect **10510**, and WDM MUXes **10050**, are controlled by the switch controller **13030**, responsive to the CTR **002**, through five bi-directional control lines **13031, 13737, 13033, 13035**, and **13034**, respectively. Each of the five

control lines provides configuration information from the switch controller **13030** to the WDM DMUXes **10040,** optical alignment subsystems **10900,** tunable lasers **10200**, optical cross connect **10510**, and WDM MUX **10050;** and via the five bi-directional control lines **13031, 13737, 13033, 13035**, and **13034**, the switch controller **13030** receives various status and control information from the WDM DMUXes **10040,** optical alignment subsystems **10900,** tunable lasers **10200**, optical cross connect **13035**, and WDM MUXes **10050**, respectively.

FIG. 25A shows the operation of a possible embodiment of optical cross connect (OXC) **10510** having a plurality of inputs **14050-1** through **14050-N** and a plurality of outputs **14055-1** through **14055-N.** In the embodiment shown in FIG. 25A each input **14050-1** through **14050-N** and each output **14055-1** through **14055-N** carries an optical signal comprising a single wavelength. The OXC switches the optical signal on any input line **14050-1** through **14050-N** to any output line **14055-1** through **14055-N.** For example, with reference to FIG. 25A, the green wavelength received through input **14050-1** is switched to and forwarded through output line **14055-2.**

The switch in FIG. 8A performs PF that is realized in two operational phases, as shown in FIG. 8B. Data units belonging to a whole time frame received from each of the optical channels during Phase 1 are switched through the switch in Phase 2. In a possible embodiment, if Phase 1 begins in time frame t, Phase 2 takes place in time frame t+1. In another embodiment, if Phase 1 ends in time frame t, Phase 2 takes place in time frame t+1. The 2-phase operation ensures that data units received from the various optical channels are aligned with the CTR before being switched. Phase 2 can be performed during either the time frame immediately following Phase 1, during time frame t+1 — immediate forwarding operation, or at a later time frame — non-immediate forwarding operation.

The input/output connection configuration within the OXC **10510** in the switching system **10000** depicted in FIG. 8A determines how many of the plurality of wavelengths of each

input **10010** are routed to each one of the plurality of the outputs **10020**. In a possible implementation, the switch controller **13030**, responsive to the CTR **002** signal, changes the configuration of the OXC **10510**, through a control signal **13035**, with a time scale much larger than a time frame. In a possible implementation, the switch controller **13030** changes the configuration of the OXC **10510** responsive to the CTR **002** signal so that the configuration is changed between two adjacent time frame, wherein in the previous one of the two time frames a first OXC configuration is deployed and the second one of the two time frames a second OXC configuration is deployed. In a possible embodiment, the change of configuration takes place during the idle time between time frames shown in FIG. 33. In an alternative embodiment, the configuration change takes a time comprising a plurality of time frames; for the time in which the OXC configuration is changed the respective selected tunable lasers **10200** do not transmit on the input lines **10520** that are involved in the configuration change. The selected tunable lasers **10200** resume transmitting at the beginning of the time frame following the time frame during which the OXC configuration change is completed.

In a possible embodiment, the OXC configuration changes reoccur periodically with a period which is an integer multiple of the time cycle or the super cycle.

In a possible implementation the number of wavelengths of each input **10010** is smaller than the number of inputs **10010**. In another possible implementation the number of wavelengths of each input **10010** is larger than the number of inputs **10010**.

In an alternative implementation of the switching system **10000** shown in FIG. 8A an alignment subsystem **10100** such as the one depicted in FIG. 4 is coupled to each wavelength of the input **10010**, as in the switch architecture presented in FIG. 1A, instead of having an optical alignment subsystem **10900** coupled to each input **10010**, as in the switch architecture shown in FIG. 8A.

Transmission of data units responsive to a common time reference **002** can deploy multiple wavelengths–also called optical channels or lambdas–across a Wavelength Division Multiplexing (WDM) link and throughout a lambda routed network. FIG. 9 shows the architecture of a communications system responsive to the common time reference wherein data units are associated to a specific time frame or sub-time frame, wherein such data units are transmitted over a specific wavelength across a WDM network **7310** whose network nodes (called wavelength routers or lambda routers) possibly route different wavelengths towards different destinations. In other words, the lambda routing network **7310** couples an optical channel on an ingress link **1230-I** with an optical channel (possibly the same optical channel if the lambda routing network **7310** does not have wavelength conversion capability) on a selected egress link **1230-E**.

The transmission system in FIG. 9 couples data units from an output port **7320** to an input port **7330** through a communications network **7310** deploying lambda routing. Within the WDM communications network **7310** multiple optical channels are multiplexed over links among nodes; nodes, also called lambda routers, route different channels over different paths. The output port **7320** and the input port **7330** are connected to the communications network **7310** through WDM links **1230-I** and **1230-E**, respectively, comprising a plurality of optical channels.

The system receives a common time reference **002** and comprises a transmission delineation controller **7325**–source of delimiter signals–responsive to the CTR **002**; a serial transmitter **6012**, responsive to the delimiter signals **6030** through **6034** and the CTR **002** for sending the control signals and the data units over a line **7345** to a tunable laser **7340**. The tunable laser **7340** transmits the bit stream received on line **7345** on the output link **1230-I** on a selected optical channel responsive to the Select-WL signal **7328**.

FIG. 10A is a timing diagram of the operation of the time driven tunable laser **7340**. The timing diagram shows a sequence of time frames **TF** of the common time reference (CTR) and

the wavelength used by the time driven tunable laser **7340** for transmitting data during each of the time frames. FIG. 10B shows the effect of the selection of a specific wavelength when the output port **7320** and the input port **7330** of the transmission system in FIG. 9 are connected to a lambda switching network **7310.** In fact the communications network **7310** routes different wavelengths entering the network from the same ingress point (e.g., the communications link **1230-I**) to different egress points (among which, for example, the communications link **1230-E**) of the communications network **7310.** For example, data units transmitted during a first respective time frame over the green wavelength are routed by the communications network **7310** to the egress point X, while data units transmitted during a second respective time frame over the yellow wavelength are routed by the communications network **7310** to egress point Y.

The system depicted in FIG. 9 further comprises a tunable optical receiver **7350** that receives data through the input link **1230-E** over a selected optical channel responsive to the Select-WL **7358.** The received data stream is passed through line **7355** to a serial receiver **6022,** responsive to the CTR **002.** The serial receiver **6022** is coupled to a receive delineation controller **7335,** responsive to the CTR **002,** through delimiter signals **6040** through **6044.** The input port **7330** in FIG. 9 further comprises an Alignment Subsystem **6600** for storing the data units received from the input link **1230-E** while sorting them out according the time frame or sub-time frame during which they were sent out of the output port **7320.**

FIG. 10C is a timing diagram of the operation of the time driven tunable optical receiver **7350** depicted in FIG. 9. The timing diagram in FIG. 10C shows a sequence of time frames **TF** of the unique time reference (UTR) of the corresponding communications link **1230-E** and the wavelength used by the time driven tunable optical receiver **7350** for receiving data during each of the time frames. FIG. 10D shows the effect of the selection of a specific wavelength when the output port **7320** and the input port **7330** in FIG. 9 are connected to a lambda switching network **7310.** The communications network **7310** can route different wavelengths entering the network

from various ingress points (among which, for example, the communications link **1230-I**) to one egress points (e.g., the communications link **1230-E**) of the communications network **7310**. For example, data units received during a first respective time frame over the green wavelength had been routed by the communications network **7310** from ingress point X, while data units received during a second respective time frame over the yellow wavelength had been routed by the communications network **7310** from ingress point Y.

The alignment subsystem **6600** in FIG. 9 receives data units over the data line **6020** from the serial receiver **6022**. The data units that exit from the alignment subsystem **6600** are transferred to the switch fabric over its input lines **940**. The control data units, namely the data units transmitted over the communications channel **920** during a control time frame, are transferred to the switch controller **13030** through line **980**.

In FIG. 1, the Transmit Delineation Controller **6011**, responsive to the CTR **002**, generates control signals **6030** through **6034** to indicate to the serial transmitter (TX) **6012** to insert control information in the data flow.

The serial transmitter **6012** receives data units over line **6010** and transmits them on the communications channel **920**. Responsive to the control signals **6030** through **6034** from the Transmit Delineation Controller **7325**, the serial transmitter **6012** combines the data units to be transmitted on the communications channel **920** with control information such as time frame delimiters, time cycle delimiters, and time stamps according to at least one of the plurality of methods to encode such information in the data stream.

Upon receiving the data stream, the serial receiver **6022** on the receiving side of the communications channel **1230-E** separates data units from control signals. The serial receiver **6022** outputs the received data units on the data line **6020** and notifies the receive delineation controller **7335** of the received control signals over the lines **6040** through **6044**.

The Transmit Delineation Controller **7325**, responsive to the CTR **002**, generates control signals **6030** through **6034** to indicate the serial transmitter (TX) **6012** to insert control information in the data flow. The Transmit Delineation Controller **7325** generates the control signals **6030** through **6034** according to predefined operation principles that aim at providing a receiving input port to identify the boundaries of TFs and time cycles.

In addition, the Transmit Delineation Controller **7325** generates the Select-WL signal **7328** to indicate the Tunable Laser **7340** on which optical channel the data units belonging to the current time frame or sub-time frame should be transmitted through the link **1230-I** at the ingress of the DWM network **7310**. Whenever, according to the common time reference **002**, a new time frame or sub-time frame is beginning, the Transmit Delineation Controller **7325** uses the Select-WL signal **7328** to select the optical channel on which the data units belonging to the current time frame or sub-time frame are going to be transmitted. The optical channel on which the data units are being transmitted determines the egress link **1230-E** from which such data units are going to exit the lambda routing network **7310** and ultimately the input port **7330** on which they are going to be received.

The Receive Delineation Controller **7335** receives the control signals **6040** through **6044** and handles them according to operation principles that aim at identifying the boundaries of TFs and time cycles.

In addition, the Receive Delineation Controller **7335** generates the Select-WL signal **7358** to indicate the Tunable Optical Receiver **7350** on which optical channel the data units belonging to the current time frame or sub-time frame should be received through the link **1230-E** at the egress of the DWM network **7310**. Whenever, according to the control signals **6040** through **6044**, a new UTR (Unique Time Reference) time frame or sub-time frame is beginning, the Transmit Delineation Controller **7325** uses the Select-WL signal **7358** to select the optical channel on which the data units belonging to the current time frame or sub-time frame are going

to be received. The data stream received over the selected optical channel are passed to the serial receiver through the line **7355**.

In an alternative embodiment, the input port **7330** comprises a fixed receiver (instead of a tunable one **7350**) or the tunable optical receiver **7350** is kept tuned on the same wavelength. In this embodiment the lambda switching network **7310** provides a wavelength merging service, i.e., a selected wavelength of an egress WDM link **1230-E** carries data units transmitted on the selected wavelength from different ingress points (among which, possibly, the WDM link **1230-I**) in different moments. In a possible embodiment, each of the time frames of the UTR of link **1230-E** carry data units transmitted from a different ingress point, i.e., the wavelength received during each of the time frames of the link **1230-E** UTR had been generated by a different respective output port **7320**.

FIG. 11A depicts the architecture of an alternative embodiment of a tunable laser-based time driven switch **10000** in which an optical star coupler **10810** and a plurality of filter&laser modules **10840** are used for interconnecting the plurality of tunable lasers **10200** with their respective ones of the WDM MUXes **10050**.

The switch **10000** in FIG. 11A performs PF that is realized in two operational phases, as shown in FIG. 11B. Data units belonging to a whole time frame received from each of the optical channels during Phase 1 are switched through the switch in Phase 2. In a possible embodiment, if Phase 1 begins in time frame t, Phase 2 takes place in time frame t+1. In another embodiment, if Phase 1 ends in time frame t, Phase 2 takes place in time frame t+1. The 2 phase operation ensures that data units received from the various optical channels are aligned with the CTR before being switched. Phase 2 can be performed during either the time frame immediately following Phase 1, during time frame t+1 — immediate forwarding operation, or at a later time frame — non-immediate forwarding operation.

FIG. 24C shows the operation of a star coupler **13010** having a single optical input **14030** and a plurality of optical outputs **14035**. The star coupler **13010** splits the optical signal, possibly comprising a plurality of wavelengths (a green, a red, and a yellow wavelength in the example depicted in FIG. 24C), entering through the input **14030** over all the outputs **14035**. In a possible embodiment of star coupler **13010** the power of the input signal is split among the output signals. In the example in FIG. 24C, each of the optical signals on the outputs **14035** has one third of the power of the optical signal on the input **14030**.

The output **10820** of each tunable laser **10200** in FIG. 11 is coupled to the star coupler **10810**. The inputs **10830** of a plurality of filter&laser modules **10840** are coupled to the star coupler **10810**. The inputs **10830** of a plurality of filter&laser modules **10840** are coupled to the star coupler **10810** so that the optical signal generated by each of the tunable lasers **10200** is received by each of the filter&laser modules **10840**.

The filter&laser module **10840** separates a selected one of the wavelengths received through its input **10830** and transmits the data units carried on the selected wavelength, possibly using a different wavelength, on its output line **10850** coupled to a respective input of a respective one of the WDM MUXes **10050**. In an alternative embodiment, a wavelength converter could be used instead of the filter&laser module **10840**, the wavelength converter converting a first selected wavelength received through the star coupler **10810** into a second selected wavelength to be combined by the WDM MUX and transmitted on the output channel **10020**.

In another possible embodiment, at least one of the outputs **10830** of the star coupler **10810** is directly coupled with a respective one of the inputs **10850** of the respective one of the WDM MUXes **10050**.

The WDM DMUXes **10040**, alignment subsystems **10100**, tunable lasers **10200**, star coupler **10810**, filter&laser modules **10840**, and WDM MUXes **10050**, are controlled by the

switch controller **13030,** responsive to the CTR **002,** through six bi-directional control lines **13031, 13032, 13033, 13036, 13037,** and **13034**, respectively. Each of the six control lines provides configuration information from the switch controller **13030** to the WDM DMUXes **10040,** alignment subsystems **10100,** tunable lasers **10200,** star coupler **10810,** filter&laser modules **10840,** and WDM MUXes **10050;** and via the six bi-directional control lines **13031, 13032, 13033, 13036, 13037,** and **13034,** the switch controller **13030** receives various status and control information from the WDM DMUXes **10040,** alignment subsystems **10100,** tunable lasers **10200,** star coupler **10810,** filter&laser modules **10840,** and WDM MUXes **10050.**

According to the architecture depicted in FIG. 11A, the wavelength used by each of the plurality of tunable lasers **10200** for transmitting determines the output link **10020** and wavelength on it that is going to carry data units to the next switching system **10000.** During each time frame, each tunable laser **10200** uses a pre-selected wavelength for transmitting data units retrieved from its respective alignment subsystem **10100.** Wavelengths used by different tunable lasers **10200** during the same time frame are different, i.e., the same wavelength is not used by more than one tunable laser **10200** during the same time frame. In order to be able to switch data units from any of the channels on any of the inputs **10010** to any of the channels to any of the outputs **10020,** each tunable laser **10200** must be able to generate at least 256 wavelengths. Specific implementations can use a smaller number of wavelengths per tunable laser **10200,** which imposes some limits on the possible input/output connections.

Data units transmitted on a selected wavelength are received by a relative one of the filter&laser modules **10840.** The system&laser module **10840** comprises a filter to separate the selected wavelength from the plurality of wavelengths carried by its input line **10830,** a receiver to receive data units carried by the wavelength and a laser to transmit them on a selected wavelength on the output line **10850.** In an alternative implementation the system&laser module

10840 comprises a filter and a wavelength converter implemented in any other way than by an optical receiver and a laser transmitter.

In an alternative implementation, the filter&laser module **10840** comprises a tunable filter and receiver that are able to separate and receive data units carried by a selected one of a plurality of wavelengths. In this embodiment, the filter&laser module **10840** is tuned responsive to the control signal **13037**, and ultimately to the CTR, on a different wavelength during each time frame. As a consequence, multicast services can be implemented by the time driven switch **10000**, whereas data units transmitted through the star coupler **10810** on a wavelength during a specific time frame by a selected tunable laser **10200** are received concurrently by a plurality of filter&laser modules **10840**, possibly connected to a plurality of WDM MUXes **10050** — i.e., a plurality of outputs **10020** — and forwarded on a plurality of wavelengths through a plurality of outputs **10020**.

In a possible implementation, each tunable laser is capable of generating a number of wavelengths equaling the total number of wavelengths of all the inputs **10010**. For example, in the configuration depicted in FIG. 11A, each tunable laser **10200** is capable of generating $16 \cdot 16 = 256$ different wavelengths. In an alternative implementation, each tunable laser is capable of generating a number of wavelengths smaller than the total number of wavelengths of all the inputs **10010**. In an alternative implementation, each tunable laser is capable of generating a number of wavelengths greater than the total number of wavelengths of all the inputs **10010**.

In a possible implementation the number of wavelengths of each input **10010** is smaller than the number of inputs **10010**. In another possible implementation the number of wavelengths of each input **10010** is greater than the number of inputs **10010**.

In an alternative implementation of the switching system **10000** shown in FIG. 11A an optical alignment subsystem **10900** such as the one depicted in FIG. 12 is coupled to each input **10010**, instead of having an alignment subsystem **10100** coupled to each channel of each input

10010. In a possible embodiment of an all-optical switch, the aforementioned optical alignment subsystems **10900** are deployed together with wavelength converters replacing the filter&laser modules **10840** and the tunable lasers **10200**.

FIG. 13A depicts the architecture of an alternative embodiment of a tunable laser-based time driven switch **10000** in which a plurality of star couplers **11010**, optical multiplexers **11020**, and filters **11030** — one for each channel — are used for interconnecting the plurality of tunable lasers **10200** with their respective ones of the WDM MUXes **10050** at the outputs **10020**.

The output of each tunable laser **10200** is coupled to a corresponding star coupler **11010**. Each star coupler **11010** has a plurality of outputs **11050**, each connected to a respective one of the plurality of outputs **10020**. Each of the output channels is coupled to an optical WDM multiplexer (MUX) **11020**. Each such optical multiplexer **11020** is connected to a plurality of star couplers **11010**, each input **11050** of the optical MUX coupled to a different input **10010**. The optical MUX **11020** combines the wavelength signals from a plurality of inputs **10010** on a single connection to a filter **11030** that selects one of the wavelengths for transmission on the respective output link **10020**. The selected wavelength is multiplexed by an optical WDM multiplexer **10050** with other 15 wavelengths before transmission on the output link **10050**.

The coupling of tunable lasers **10200**, star couplers **11010**, MUXes **11020**, and filters **11030** enables data units to be switched from any of the input channels to any of the output channels. Moreover, it enables data units form multiple channels on the same input **10010** to be switched to multiple channels of the same output **10020**, during the same TF.

Each of the plurality of filters **11030** connected to the same output WDM MUX **10050** allows a single fixed wavelength to reach the corresponding WDM MUX **10050**. The frequencies allowed by all the filters **11030** connected to the same WDM MUX **10050** are all different from each other. The frequencies allowed by the filters **11030** coupled to the same star coupler **11010**, i.e., to the same TL **10200** and input channel, are all different from one another.

The switch in FIG. 13A performs PF that is realized in two operational phases, as shown in FIG. 13B. Data units belonging to a whole time frame received from each of the optical channels during Phase 1 are switched through the switch in Phase 2. In a possible embodiment, if Phase 1 begins in time frame t, Phase 2 takes place in time frame t+1. In another embodiment, if Phase 1 ends in time frame t, Phase 2 takes place in time frame t+1. The 2 phase operation ensures that data units received from the various optical channels are aligned with the CTR before being switched. Phase 2 can be performed during either the time frame immediately following Phase 1, during time frame t+1 — immediate forwarding operation, or at a later time frame — non-immediate forwarding operation.

Each tunable laser **10200** in FIG. 13A changes the transmitting wavelength at each TF according to a predefined pattern that repeats each time cycle or super cycle. The wavelength to be used during each TF is chosen at the time of setting up a fractional lambda pipe (FLP). For each input channel, the wavelength used by the corresponding tunable laser (TL) **10200** determines the output **10020** on which the data units transmitted during the TF are going to be forwarded. In fact, since all the filters **11030** coupled to one TL **10200** are different, only one of the plurality of filters **11030** allows the wavelength generated by the TL **10200** to reach the corresponding WDM MUX **10050**; i.e., the wavelength generated by each selected TL **10200** reaches only one WDM MUX **10050** to be multiplexed onto only one output **10020.**

The WDM DMUXes **10040,** alignment subsystems **10100,** tunable lasers **10200,** star couplers **11010,** MUXes **11020,** filters **11030,** and WDM MUXes **10050,** are controlled by the switch controller **13030,** responsive to the CTR **002,** through seven bi-directional control lines **13031, 13032, 13033, 13036, 13039, 13038,** and **13034**, respectively. Each of the seven control lines provides configuration information from the switch controller **13030** to the WDM DMUXes **10040,** alignment subsystems **10100,** tunable lasers **10200,** and WDM MUXes **10050;** and via the seven bi-directional control lines **13031, 13032, 13033, 13036, 13039, 13038,** and

13034, the switch controller **13030** receives various status and control information from the WDM DMUXes **10040**, alignment subsystems **10100**, tunable lasers **10200**, star couplers **11010**, MUXes **11020**, filters **11030**, and WDM MUXes **10050**.

The switching system **10000** embodiment presented in FIG. 13A requires each TL **10200** to be capable of generating a total of 16 different wavelengths, one for each one of the outputs **10020**. Analogously, the embodiment in FIG. 13A requires 16 different filters **11030**, one for each one of the outputs **10020**, each different filter having a passband including one of 16 different wavelengths.

The switching system architecture depicted in FIG. 13A requires tunable lasers **10200** to operate with a smaller number of wavelengths than the switching system architecture depicted in FIG. 11A (16 wavelengths and 256 wavelengths, respectively). However, while the switching system in FIG. 11A is non-blocking — i.e., during each TF it is possible to transfer data units from any one of the input channels to any one of the idle output channels —, the switching system in FIG. 13A is blocking — during a TF it might not be possible to switch data units from a selected input channel to a specific output channel.

In an alternative embodiment, each TL **10200** and its corresponding star coupler **11010**, is coupled to a subset of the output WDM MUXes **10050** through the lines **11050**, WDM MUXes **11020**, and filters **11030**. Similarly, each of the MUXes **11020** is coupled to a subset of the inputs **10010** through the lines **11050**. This configuration reduces the flexibility of the switching system **10000** by introducing constraints on the output channels on which data units received on each respective input channel can be forwarded. However, in this configuration each star coupler **11010** has a smaller number of output lines **11050** and, as a consequence, introduces a smaller attenuation between the input, i.e., the signal generated by the corresponding tunable laser **10200** and each output line **11050**. Moreover, the number of wavelengths each TL **10200** is required to generate is smaller.

Multicasting can be achieved with an alternative embodiment of the architecture showed in FIG. 13A by deploying tunable filters, responsive to the CTR, instead of static filters **11030.** During each time frame the passband of each tunable filter can be changed to include a different wavelength. This enables the data units transmitted by a TL **10200** through its corresponding star coupler **11010** to reach more than one output WDM MUX **10050** and to be forwarded on more than one output **10020.**

In an alternative implementation of the switching system **10000** shown in FIG. 13A an optical alignment subsystem **10900** such as the one depicted in FIG. 12 is coupled to each input **10010,** instead of having an alignment subsystem **10100** coupled to each channel of each input **10010.** In a possible embodiment of an all-optical switch, the aforementioned optical alignment subsystems **10900** are deployed together with wavelength converters replacing the tunable lasers **10200.**

<u>**Time Driven Tunable Wavelength Conversion-Based Switching with Common Time Reference**</u>

Advances in components for optical networking have led to the realization of dynamic optical switch fabrics — e.g., based among others on electro-mechanical micro mirrors, holographic techniques, bubbles —, tunable lasers, tunable receivers, wavelength converters, and tunable wavelength converters. The time required for changing the input/output configuration of dynamic optical switch fabrics is currently larger than the time required for changing the wavelength received by a tunable receiver, the wavelength transmitted by a tunable laser, and the wavelength emitted by a tunable wavelength converter. As a consequence, optical switch architectures based on tunable receivers, tunable lasers, and tunable wavelength converters, rather than optical switch fabrics, are appealing. The present disclosure describes a number of optical switch architectures based on wavelength conversion achieved through the deployment of at least one of tunable receivers, tunable lasers, and tunable wavelength converters.

Architectures based on tunable wavelength converters can be appealing especially because they can provide all-optical solutions for scenarios and applications in which similar architectures deploying electronic components fail to provide the needed scalability.

FIG. 14 is the architecture of a possible embodiment of a time driven switch **13000** based on a wavelength conversion (WLC) subsystem **13100**. The switching system **13000** presented in FIG. 14 has a plurality of inputs **10010** and outputs **10020**, each one comprised of at least one optical link with a plurality of wavelengths. The switching system **13000** in FIG. 14 comprises a switch controller **13030**, a plurality of optical alignment subsystems **10900**, star couplers **13010**, WLC subsystems **13100**, and wavelength division multiplexers (WDMs) **10050**, and an optical interconnection subsystem **13020** coupling selected ones of the WLC subsystems **13100** to at least one of the wavelength division multiplexers **10050**.

An optical alignment subsystem **10900** is associated with each respective one of the inputs **10010**. The optical alignment subsystem **10900** aligns to the common time reference (CTR) data units transported over the plurality of wavelengths of its respective input **10010**.

A star coupler **13010** is associated with each input **10010**. It forwards the signal received through its input **10010**, i.e., all the wavelengths carried by the optical link coupled to its respective input **10010**, on all of its output lines **13040** to a plurality of WLC subsystems **13100**. In the embodiment presented in FIG. 14, the number of WLC subsystems **13100** connected to each star coupler **13010** is the same as the number of switch outputs **10020**. An alternative embodiment comprises a number of WLC subsystems **13100** per star coupler **13010** smaller than the number of outputs **10020**. Another alternative embodiment comprises a number of WLC subsystems **13100** per star coupler **13010** larger than the number of outputs **10020**.

The optical alignment subsystems **10900**, star couplers **13010**, WLC subsystems **13100**, optical interconnection subsystem **13020**, and WDM MUXes **10050**, are controlled by the switch controller **13030**, responsive to the CTR **002**, through five bi-directional control lines **13737**,

13036, **13041**, **13042**, and **13034**, respectively. Each of the five control lines provides configuration information from the switch controller **13030** to the optical alignment subsystems **10900**, star couplers **13010**, WLC subsystems **13100**, optical interconnection subsystem **13020**, and WDM MUXes **10050**; and via the five bi-directional control lines **13737**, **13036**, **13041**, **13042**, and **13034**, the switch controller **13030** receives various status and control information from the optical alignment subsystems **10900**, star couplers **13010**, WLC subsystems **13100**, optical interconnection subsystem **13020**, and WDM MUXes **10050**.

Each WLC subsystem **13100** converts a specific wavelength, responsive to the CTR **002**. FIG. 15A shows a possible embodiment of a WLC subsystem **13100** comprising a wavelength conversion (WLC) scheduling controller **13120** responsive to the CTR **002** and to a wavelength mapping table **13110** downloaded from the switch controller **13030** through the bi-directional control line **13041**, and a tunable wavelength conversion subsystem **13150** responsive to a signal **13140** from the WLC scheduling controller **13120**.

As shown by the switch architecture depicted in FIG. 14, the tunable wavelength conversion subsystem **13150** within the WLC subsystem **13100** in FIG. 15A is connected to a respective one of the output lines **13040** of a respective one of the star couplers **13010** from which the tunable wavelength conversion subsystem **13150** receives an optical signal comprising a plurality of wavelengths. During each time frame of the CTR the tunable wavelength conversion subsystem **13150** is tuned by the Color control signal **13140** to convert a first selected wavelength, i.e., color, into a second selected wavelength sent out on the output line **13510**.

The second selected wavelength emitted on the output line **13510** of the tunable wavelength conversion subsystem **13150** as a result of the conversion of the first wavelength received on its input line **13040** carries the same information as the first wavelength.

In a possible embodiment the color control signal **13140** selects a different first wavelength for conversion by the tunable wavelength conversion subsystem **13150** during each

time frame. In a possible embodiment the tunable wavelength conversion subsystem **13150** converts the first selected wavelength into a second fixed wavelength during each time frame. In an alternative embodiment the tunable wavelength conversion subsystem **13150** converts the first selected wavelength into a second wavelength that can be different during each time frame. FIG. 15B is a sample timing diagram describing the operation of the aforementioned alternative embodiment of tunable wavelength conversion subsystem **13150.** The timing diagram shows a sequence of CTR time frames **TF** and for each time frame a first selected wavelength on data line **13040** being converted into a second selected wavelength emitted on data line **13510,** wherein each wavelength is identified by the color (green, yellow, red, and blue) of the corresponding light beam. For example, in the leftmost time frame shown in the timing diagram depicted in FIG. 15B the green wavelength is converted into the blue wavelength, i.e., during the leftmost time frame the blue light beam on data line **13510** carries the same information as the green light beam on data line **13040.**

In an alternative embodiment the color control signal **13140** selects a different wavelength for conversion by the tunable wavelength conversion subsystem **13150** during each sub-time frame.

The Color control signal **13140** is generated by the WLC scheduling controller **13120** according to the content of the wavelength mapping table **13110** that indicates the wavelength on which data units should be received during each TF. In a possible embodiment the wavelength mapping has a predefined pattern that is repeated every time cycle and super cycle. When the WLC subsystem **13100** in FIG. 15 is deployed in the architecture shown in FIG. 14, the mapping information contained in the wavelength mapping table **13110** determines the route within the switching system **13000** of the data units carried over the plurality of optical channels during each time frame. In a possible embodiment the content of the wavelength mapping table **13110** is updated whenever a FLP is created or torn down.

In a possible embodiment, the above mentioned mapping repeats each time cycle or each super cycle.

An alternative embodiment features a centralized WLC scheduling controller that generates the color control signal **13140** for all the tunable wavelength conversion subsystems **13100** in the respective switching system. In a possible implementation of such an embodiment the centralized WLC scheduling controller is within the switch controller **13030** depicted in FIG. 14.

FIG. 19A shows a possible implementation **13500** of the optical interconnection subsystem **13020**. When this optical interconnection subsystem **13500** is deployed in the architecture depicted in FIG. 14, each connection line **13050** within the optical interconnection subsystem **13500** couples the optical signal emitted by a respective WLC subsystem **13100** on data line **13510** with a fixed WDM multiplexer (MUX) **10050** associated to a fixed specific output **10020**. In the embodiment presented in FIG. 14, each of the outputs **13040** of a star coupler **13010** is coupled, through a WLC subsystem **13100** and the connection within the optical interconnection subsystem **13500** to a different switch output **10020**. Consequently, data units received through a switch input **10010** can be forwarded on any output **10020**. However, due to the fixed connections between WLC subsystems **13100** and output WDMs **10050**, during each time frame only data units carried on one wavelength on each input **10010** can be transferred to a given output **10020**. In other words, it is not possible to transfer to the same output **10020** data units received on two different wavelengths carried on the same input fiber. In order to transfer data units carried on a first wavelength to a first output **10020**, the WLC subsystem **13100** connected through its respective line **13510** to the WDM **10050** of the first output **10020** is to be tuned on the first wavelength.

FIG. 24B shows the operation of a WDM **10050** receiving a plurality of wavelengths, i.e., colors (green, red, and yellow in the example in FIG. 24B), on its respective inputs **14025**. The

WDM **10050** combines all of the wavelengths into a single optical signal comprising the plurality of wavelength onto its output **14020.** In the example in FIG. 24B, the green wavelength received from the top input **14025**, the red wavelength received from the middle input **14025**, and the yellow wavelength received from the lower input **14025** are combined and emitted on the output **14020.**

In the architecture depicted in FIG. 14 all the WLC subsystems **13100** connected to the same WDM **10050** emit a different wavelength. The WDM **10050** multiplexes on the same output fiber **10020** all the wavelengths received from its respective WLC subsystems **13100** through its respective lines **13520.**

In a possible embodiment of WLC subsystem, the wavelength emitted on its output data line **13510** is fixed. Hence, in the embodiment of switching system **13000** as in FIG. 14 deploying the optical interconnection subsystem **13500** shown in FIG. 19A each wavelength on a switch output **10020** is uniquely associated to a specific one of the switch inputs **10010.** Consequently, a WLC subsystem **13100** in a first switch **13000** tuned to convert a first wavelength determines that data units that have reached a second upstream switch through a first input **10010** (as shown by the timing diagram in FIG. 16C) uniquely associated to the first wavelength are going to be forwarded by the first switch through the output **10020** associated to the WLC subsystem.

The switching system **13000** architecture shown in FIG. 14 provides multicast transmission capability in that it is possible to transmits on more than one output **10020** data units received on the same wavelength of a first input **10010.** Multicasting is achieved by tuning the WLC subsystems **13100** coupled to the selected outputs **10020** to convert the same wavelength.

In a possible implementation the number of wavelengths of each input **10010** is smaller than the number of inputs **10010.** In another possible implementation the number of wavelengths of each input **10010** is smaller than the number of inputs **10010.**

FIG. 16A depicts the block diagram **13200** of a possible embodiment of tunable wavelength conversion subsystem **13150** comprising a tunable receiver (TR) **13210** and a fixed laser **13220.**

During each time frame of the CTR the receiver **13210** is tuned by the Color control signal **13140** to receive data units carried by a specific wavelength, i.e., color. Received data units are sent out towards the laser **13220** for being transmitted on a fixed wavelength.

FIG. 16B contains a timing diagram showing the operation of the tunable receiver **13210.** The timing diagram shows the wavelength on which the receiver **13210** receives data units during each time frame of the CTR, responsive to the Color signal **13140** from the WLC scheduling controller **13120.**

In a possible embodiment the color control signal **13140** selects a different wavelength for reception of data units by the tunable receiver **13210** during each time frame. FIG. 15B is a sample timing diagram describing the operation of a tunable receiver **13210** in this embodiment. The timing diagram shows a sequence of CTR time frames **TF** and for each time frame the wavelength on which data units are received by the tunable receiver **13210,** wherein each wavelength is identified by the color (green, yellow, red, and blue) of the corresponding light beam.

In an alternative embodiment the color control signal **13140** selects a different wavelength for reception of data units by the tunable receiver **13210** during each sub-time frame.

When the embodiment **13200** of tunable wavelength conversion subsystem **13150** presented in FIG. 16A is deployed in a WLC subsystem **13100** within the switch **13000** architecture depicted in FIG. 14, the lasers **13220** of all the WLC subsystems **13100** coupled to

the same WDM **10050** transmit on a different wavelength. The WDM **10050** multiplexes on the same output fiber **10020** all the wavelengths received from its respective lasers **13020** through its respective lines **13030**. Hence, each wavelength on a switch output **10020** is uniquely associated to a specific one of the switch inputs **10010**. Consequently, a tunable receiver **13100** in a first switch **13000** tuned to receive data units on a first wavelength determines that data units that have reached a second upstream switch through a first input **10010** (as shown by the timing diagram in FIG. 16C) uniquely associated to the first wavelength are going to be forwarded by the first switch through the output **10020** associated to the tunable receiver.

FIG. 17A shows a possible architecture **13300** for an alternative embodiment of tunable wavelength conversion subsystem **13150** that can be used in the WLC subsystem **13100** within the switching system **13000** presented in FIG. 14. The tunable wavelength conversion subsystem **13300** in FIG. 17A comprises a tunable wavelength converter (TWLC) **13310** responsive to the color control signal **13140** from the WLC scheduling controller **13120**. The color control signal **13140** indicates the wavelength to be converted by the TWLC **13310**. The TWLC **13310** receives an optical signal on line **13040**. Such optical signal possibly comprises a plurality of wavelengths.

In a possible embodiment, the TWLC **13310** converts the wavelength channel identified by the color control signal **13140** in a fixed wavelength signal on line **13510** coupled to a respective one of the output WDMs **10050**.

In the preferred embodiment of the present invention the color control signal **13140** selects a different wavelength (color) for being converted by the TWLC **13310** during each time frame. FIG. 17B is a sample timing diagram describing the operation of a TWLC **13310** in this embodiment. The timing diagram shows a sequence of CTR time frames **TF** and for each time frame the wavelength to be converted by the TWLC **13310**, wherein each wavelength is identified by the color (green, yellow, red, and blue) of the corresponding light beam.

In an alternative embodiment the color control signal **13140** selects a different wavelength for being converted by the TWLC **13310** during each sub-time frame.

In an alternative embodiment, the TWLC **13330** converts the first selected wavelength signal specified by the color control signal **13140** in a second selected wavelength signal specified by the color control signal **13140.** The wavelength to be converted and the wavelength resulting from the conversion can be changed each time frame, as shown in the timing diagram depicted in FIG. 15B.

The WLC scheduling controller **13120** depicted in FIG. 15A controls the color signal **13140**, and ultimately the TWLC **13310** responsive to the CTR **002** and to a wavelength mapping table **13110.** The wavelength mapping table **13110** depicted in FIG. 15A contains the mapping between each time frame and the wavelength to be converted during the time frame. The mapping can be periodic repeating every time cycle and super cycle, as defined by the CTR.

An alternative embodiment features a centralized WLC scheduling controller that generates the color control signal **13140** for all the TWLCs **13310** in the respective switching system. In such an embodiment the centralized WLC scheduling controller can be implemented within the switch controller **13030** depicted in FIG. 14.

FIG. 18A shows a possible architecture **13400** for an alternative implementation of tunable wavelength conversion subsystem **13150** that can be used in the WLC subsystem **13100** in FIG. 15 within the switching system **13000** presented in FIG. 14. The tunable wavelength conversion subsystem **13400** in FIG. 18A comprises a tunable receive (TR) **13210** and a tunable laser (TL) **13410,** both responsive to the color control signal **13140** from the WLC scheduling controller **13120.** The color control signal **13140** indicates the wavelength on which data units are to be received by the TR **13210** and the wavelength to be generated by the TL **13410** for transmitting the data units previously received by the TR **13210.** The TR **13210** receives an optical signal on line **13040.** Such optical signal possibly comprises a plurality of wavelengths.

In an embodiment, the TR **13330** receives data units on the wavelength signal specified by the color control signal **13140** and the TL **13410** transmits them using another wavelength signal specified by the color control signal **13140**. The wavelength to be received and the wavelength to be transmitted can be changed each time frame, as shown in the timing diagram depicted in FIG. 18B.

The WLC scheduling controller **13120** controls the color signal **13140**, and ultimately the TR **13210** and TL **13410** depicted in FIG. 18A responsive to the CTR **002** and to a wavelength mapping table **13110**, as shown in FIG. 15. The wavelength mapping table **13110** contains the mapping between each time frame and the wavelength to be received during the time frame. The mapping can be periodic repeating every time cycle and super cycle, as defined by the CTR.

An alternative embodiment features a centralized WLC scheduling controller that generates the color control signal **13140** for all the TRs **13310** and TLs **13410** in the respective switching system. In such an embodiment the centralized WLC scheduling controller can be implemented within the switch controller **13030** included in the switch architecture depicted in FIG. 14.

In the preferred embodiment of the present invention the color control signal **13140** selects a different wavelength (color) for being received by the TR **13210** and a different wavelength to be generated by the TL **13410** during each time frame. FIG. 18B is a sample timing diagram describing the operation of this embodiment of tunable wavelength conversion subsystem **13400**. The timing diagram shows a sequence of CTR time frames **TF** and for each time frame the wavelength to be received **(R:)** by the TR **13210** and the wavelength to be generated **(T:)** by the TL **13410**, wherein each wavelength is identified by the color (green, yellow, red, and blue) of the corresponding light beam.

In an alternative embodiment the color control signal **13140** selects a different wavelength for reception by the TR **13210** and for transmission by the TL **13410** during each sub-time frame.

FIG. 18C depicts the block diagram **13450** of a possible embodiment of tunable wavelength conversion subsystem **13150** comprising an alignment subsystem **10100**, a tunable receiver (TR) **13210** and a fixed laser **13220**.

During each time frame of the CTR the receiver **13210** in FIG. 18C is tuned by the Color control signal **13140** to receive data units carried by a specific wavelength, i.e., color. Received data units are stored in the alignment subsystem **10100** that aligns them to the CTR responsive to the CTR signal **002**. Data units are retrieved from the alignment subsystem **10100** to be transmitted by the laser **13220** on a fixed wavelength.

FIG. 15B contains a timing diagram showing the operation of the tunable receiver **13210** in FIG. 18C. The timing diagram shows the wavelength on which the receiver **13210** receives data units during each time frame of the CTR, responsive to the Color signal **13140** from the WLC scheduling controller **13120** depicted in FIG. 15.

In a possible embodiment the color control signal **13140** selects a different wavelength for reception of data units by the tunable receiver **13210** during each time frame. FIG. 15B is a sample timing diagram describing the operation of a tunable receiver **13210** in this embodiment. The timing diagram shows a sequence of CTR time frames **TF** and for each time frame the wavelength on which data units are received by the tunable receiver **13210**, wherein each wavelength is identified by the color (green, yellow, red, and blue) of the corresponding light beam.

In an alternative embodiment the color control signal **13140** selects a different wavelength for reception of data units by the tunable receiver **13210** during each sub-time frame.

When the embodiment **13450** of tunable wavelength conversion subsystem **13150** presented in FIG. 18C is deployed in a WLC subsystem **13100** within a switching system, an architecture derived from the one depicted in FIG. 14 is used. The switching system deploying the embodiment **13450** of tunable wavelength conversion subsystem **13150** presented in FIG. 18C does not need the optical alignment subsystems **10900** on the inputs **10010**, as shown in FIG. 14, since alignment is performed by the alignment subsystem **10100** within the tunable wavelength conversion subsystem **13450**.

In a switching system architecture such as the one depicted in FIG. 14, deploying at least one of the embodiments of tunable wavelength conversion subsystem presented in FIG. 18A and 18C within the WLC subsystems **13100**, the lasers **13220** of all the WLC subsystems **13100** connected to the same WDM **10050** transmit on a different wavelength. The WDM **10050** multiplexes on the same output fiber **10020** all the wavelengths received from its respective lasers **13020** through its respective lines **13030**. Hence, each wavelength on a switch output **10020** is uniquely associated to a specific one of the switch inputs **10010**. Consequently, a tunable receiver **13100** in a first switch **13000** tuned to receive data units on a first wavelength determines that data units that have reached a second upstream switch through a first input **10010** (as shown by the timing diagram in FIG. 16C) uniquely associated to the first wavelength are going to be forwarded by the first switch through the output **10020** associated to the tunable receiver.

FIG. 19B depicts an alternative embodiment of optical interconnection subsystem **13020** to be deployed within an architecture of wavelength conversion-based time driven switch **13000** such as the one depicted in FIG. 14. The alternative embodiment of optical interconnection subsystem **13020** consists in an optical cross connect (OXC) **10510**. When the optical cross connect (OXC) **10510** is deployed in the switching system **13000** depicted in FIG. 14, it interconnects each one of the plurality of WLC subsystems **13100** to its respective one of the

WDMs **10050**. The output **13510** of each WLC subsystem **13100** is coupled to an input line of the optical cross connect **10510**. Each of the inputs **13520** of each WDM is coupled to a selected output of the optical cross connect **10510**. In the preferred embodiment the WLC subsystem **13100** is tuned to emit different wavelengths; when the optical cross connect is configured to connect the output **13510** of a WLC subsystem **13100** with a selected input **13520** of a WDM **10050**, the wavelength emitted by the WLC subsystem **13100** might have to be changed in order to avoid that the optical signal on more than one of the plurality of inputs **13520** of the selected WDM **10050** has the same wavelength.

The optical cross connect **10510** is implemented using optical switching technologies such as, but not limited to, micro electro-mechanical system (MEMS) mirrors, bubbles, holography. The optical cross connect **10510** is capable of changing the connections between its inputs **13510** and outputs **13520** responsive to a control signal **13035** from the switch controller **13030** (depicted in FIG. 14) responsive to the CTR signal **002**.

The input/output connection configuration within the OXC **10510** determines how many of the plurality of wavelengths of each input **10010** are routed to each one of the plurality of the outputs **10020**. In a possible implementation, the switch controller **13030**, responsive to the CTR signal **002**, changes the configuration of the OXC **10510** with a time scale much larger than a time frame. In a possible implementation, the switch controller **13030** changes the configuration of the OXC **10510** responsive to the CTR **002** so that the configuration is changed between two adjacent time frames, wherein in the previous one of the two time frames a first OXC configuration is deployed and the second one of the two time frames a second OXC configuration is deployed. In a possible embodiment the configuration change takes place during the idle time between aligned time frames **4140a** pictorially shown in FIG. 33.

In a possible embodiment, each configuration change takes a time comprising a plurality of time frames; for the time in which the OXC configuration is changed the respective selected

WLC subsystems **13100** in FIG. 14 do not emit on the input lines **13510** that are involved in the configuration change an optical signal carrying data units to be switched. The selected WLC subsystems **13100** resume emitting an optical signal carrying data units to be switched at the beginning of the time frame following the time frame during which the OXC configuration change is completed.

The OXC configuration changes can reoccur periodically with a period which is an integer multiple of the time cycle or the super cycle.

In a possible implementation the number of wavelengths of each input **10010** is smaller than the number of inputs **10010**. In another possible implementation the number of wavelengths of each input **10010** is smaller than the number of inputs **10010**. In another possible implementation the number of wavelengths of each input **10010** is he same as the number of inputs **10010**.

FIG. 20 depicts an alternative embodiment **13600** of optical interconnection subsystem **13020** to be deployed within an architecture of wavelength conversion-based time driven switch such as the one depicted in FIG. 14. The alternative embodiment **13600** of optical interconnection subsystem **13020** comprises a plurality of star couplers **13610**, a plurality of WDM multiplexers (WDMs) **13630**, a plurality of optical filters **13640**, and a plurality of interconnections **13620** between the star couplers **13610** and the respective WDMs **13630**.

FIG. 25C shows the operation of an optical filter **13640**, such as the ones deployed in the optical interconnection subsystem **13020** depicted in FIG. 20, that receives on its input **14040** an optical signal comprising a plurality of wavelengths (green, red, and yellow in the example shown in FIG. 25C) and emits on its output **14045** only a selected one (yellow in the example in FIG. 24C) of said plurality of wavelengths.

When the embodiment **13600** of optical interconnection subsystem **13020** shown in FIG. 20 is deployed in the switching system **13000** depicted in FIG. 14, each star coupler **13610** is

coupled to all of the outputs **10020**. In an alternative embodiment of optical interconnection subsystem **13600** each star coupler **13610** is coupled to a subset of the output WDMs **10050**. In the preferred embodiment, shown in FIG. 20, each star coupler **13610** is coupled to one WDM **13630** for each of the outputs **10020**. In an alternative embodiment, each star coupler **13610** is coupled to a plurality of WDMs **13630** for at least one of the outputs **10020**.

In the preferred embodiment, shown in FIG. 20, each star coupler **13610** is coupled through a plurality of lines **13620** to a respective predefined set of WDMs **13630**, each WDM **13630** of the respective predefined set coupled to a filter **13640**. Each WDM **13630** receives wavelength signals from a plurality of star couplers **13610**. When this embodiment **13600** of optical interconnection subsystem **13020** is deployed in the switching system **13000** depicted in FIG. 14, the 16 star couplers **13610** coupled to the same WDM **13630** through their respective line **13620** are coupled to different inputs **10010**, one star coupler **13610** for each input **10010**. In an alternative embodiment, each WDM **13630** is associated to a plurality of star couplers **13610**, each one coupled to a different input **10010**, wherein the total number of star couplers **13610** is smaller than the total number of inputs **10010**. In another alternative embodiment, each WDM **13630** is associated to a plurality of star couplers **13610**, wherein at least two of the plurality of star couplers **13610** are coupled to the same input **10010**.

Each WDM **13630** in FIG. 20 combines the wavelength signals received on all its inputs **13620** in a composite optical signal, comprised of a plurality of wavelengths, that is fed to its respective filter **13640**. In order for a switching system **13000**, such as the one depicted in FIG. 14, to operate properly, the optical signals carried by each of the lines **13620** connected to the same WDM **13630** must have a different wavelength. Consequently, the WLC subsystems **10200** in FIG. 14 coupled, through their respective star coupler **13610**, to the same WDM **13630** must not generate the same wavelength during the same time frame. This is guaranteed by properly

setting the respective wavelength mapping table **13310** to which each WLC subsystem **10200** is responsive, as shown FIG. 15A.

Each filter **13640** in FIG. 20 receives the composite optical signal, comprised of a plurality of wavelengths, from its respective WDM **13630** and allows on its output **13520** only a selected one of the wavelengths. The other wavelengths comprising the composite optical signal are filtered out. In order for the system to work properly, all the filters **13640** coupled to the same output WDM **10050**, as shown in FIG. 14, allow different wavelengths on their respective output lines **13520**.

The filters **13640** connected to the WDMs **13630** coupled to a selected one of the star couplers **13610** in FIG. 20 allow different wavelengths on their respective output line **13520**. In other words, there are no two or more filters **13640** coupled to a selected one of the star couplers **13610** that allow the same wavelength signal on their respective output line **13520**. Consequently, when data units carried by a first optical wavelength signal received on a first switch input **10010** are to be switched to a first switch output **10020** during a first time frame, the respective WLC subsystem **13100** associated to the first output **10020** is tuned to convert the first wavelength into a second wavelength, wherein the second wavelength is the wavelength not filtered out (i.e., allowed) by the respective first filter **13640** connected to both the star coupler **13610** associated to the respective WLC subsystem **13100**, and the WDM **10050** coupled to the first output **10020**. In order to ensure proper operation of the switching system **13000**, the WLC subsystems **13100** coupled, through their respective star coupler **13610**, to the first filter **13640** are tuned to transmit on a wavelength different from the second wavelength during the first time frame.

According to the architecture depicted in FIG. 14, the wavelength (color) to which a WLC subsystem **13100** is tuned in a first switching system **13000** during a first selected time frame determines the input **10010** of a second upstream switching system **13000** from which the

wavelength signal had been forwarded to the first switching system **13000**, wherein one of the inputs **10010** of the first switching system **13000** is coupled to one of the outputs **10020** of the second switching system **13000**. The wavelength (color) emitted by a WLC subsystem in the first switching system **13000** during the first selected time frame determines the output **10020** of the first switching system **13000** through which the wavelength signal is being forwarded. In other words, routing of the data units traversing one or more switching systems **13000** is determined by the tuning of the WLC subsystem **13100** comprised in each switching system **13000**, i.e., by determining the wavelength to be converted and the wavelength generated as a result of the conversion.

In the embodiment **13600** of optical interconnection subsystem **13020** for a switching system **13000** such as the one presented in FIG. 14, each of the outputs **13040** of a star coupler **13010** is coupled, through a respective WLC subsystem **13100** and star coupler **13610** to every switch output **10020**. Consequently, data units received through any switch input **10010** can be forwarded through any output **10020**. Moreover, due to the topology of the connections **13620**, the operation of the WDMs **13630**, and the filters **13640**, during each time frame multiple wavelength signals received through the same input **10010** can be transferred to a selected output **10020**. In other words, it is possible to transfer to the same output **10020** data units received on two different wavelengths carried by the same input fiber.

The switching system **13000** in FIG. 14 deploying the embodiment **13600** of optical interconnection subsystem **13020** depicted in FIG. 20 provides multicast transmission capability if the filters **13640** connected to the output WDMs **10050** can be tuned to allow different wavelength signals during different time frames. Multicasting from a first input **10010** to a first set of outputs **10020** is achieved by tuning during a first time frame the tunable filters **13640** coupled to the first set of outputs **10020** to allow a first wavelength. The WLC subsystem **13100** coupled to the first input **10010** is tuned to emit the first wavelength during the first time frame.

In order to assure proper operation, during the first time frame all the other WLC subsystems **13100** coupled to the tunable filters **13640** coupled to the first set of outputs **10020** are tuned to generate a wavelength different from the first wavelength.

In a possible embodiment of the switching system **13000** depicted in FIG. 14, all the WLC subsystems **13100** are able to emit the same set of wavelengths, wherein the total number of wavelength each WLC subsystem **13100** is able to generate is equal to the number of outputs **10020**. In an alternative embodiment, there are at least two different types of WLC subsystems **13100**, wherein WLC subsystems **13100** of the first type are able to generate a first set of wavelengths and WLC subsystems **13100** of the second type are able to generate a second set of wavelengths and so on, wherein the total number of wavelength in each set of wavelength is equal to the number of outputs **10020**. In an alternative embodiment, the number of wavelengths in each set of wavelengths is greater than the number of outputs **10020**. In an alternative embodiment, the number of wavelengths in each set of wavelengths is smaller than the number of outputs **10020**. In an alternative embodiment, the number of wavelengths in at least one set of wavelengths is different than the number of wavelengths in the other sets of wavelengths.

In an alternative implementation the number of wavelengths of each input **10010** is smaller than the number of inputs **10010**. In another possible implementation the number of wavelengths of each input **10010** is greater than the number of inputs **10010**. In another possible implementation the number of wavelengths of each input **10010** is the same as the number of inputs **10010**.

FIG. 21 is the architecture of a possible embodiment **13700** of a time driven switch based on multiple wavelength conversion (WLC) subsystems **13800** and a waveguide grating router (WGR), also called waveguide grating router **13740**. The switching system **13700** presented in FIG. 21 has a plurality of inputs **10010** and outputs **10020**, each one consisting of an optical link with a plurality of wavelengths. The switching system **13700** in FIG. 21 comprises a switch

controller **13730**, a plurality of optical alignment subsystems **10900**, multiple WLC subsystems **13800**, and one WGR **13740**.

The optical alignment subsystems **10900**, multiple WLC subsystems **13800**, and a WGR **13740** are controlled by the switch controller **13730**, responsive to the CTR **002**, through three bi-directional control lines **13737**, **13735**, and **13736**, respectively. Each of the three control lines provides configuration information from the switch controller **13730** to the optical alignment subsystems **10900**, multiple WLC subsystems **13800**, and the WGR **13740**; and via the three bi-directional control lines **13737**, **13735**, and **13736**, the switch controller **13730** receives various status and control information from the optical alignment subsystems **10900**, multiple WLC subsystems **13800**, and the WGR **13740**.

FIG. 25B illustrates the operation of a WGR **13740**. The WGR **13740** depicted in FIG. 25B has three inputs **14060-1**, **14060-2**, and **14060-3** and three outputs **14065**, each one consisting of an optical link with three wavelengths (**green**, **red**, and **blue**). The optical signal consisting of the **green** wavelength received on input **14060-1** is switched to output **14065-1**, the optical signal consisting of the **red** wavelength received on input **14060-1** is switched to output **14065-2**, and optical signal consisting of the **blue** wavelength received on input **14060-1** is switched to output **14065-3**. In a similar way, each wavelength on input **14060-2** and **14060-3** is switched separately, one wavelength to each one of the outputs **14065-1**, **14065-2**, and **14065-3**, as shown in FIG. 25B.

In the switching system architecture **13700** depicted in FIG. 21 an optical alignment subsystem **10900** is associated to each respective one of the inputs **10010**. The optical alignment subsystem **10900** aligns to the common time reference (CTR) data units transported over the plurality of wavelengths of its respective input **10010**.

As shown in FIG. 21, a multiple WLC subsystem **13800** is coupled to a selected one of the plurality of optical alignment subsystem **10900**. The multiple WLC subsystem **13800**

converts a specific set of wavelengths, responsive to the CTR signal **002**. FIG. 22A shows a possible embodiment of a multiple WLC subsystem **13800** comprising a multiple wavelength conversion (MWLC) scheduling controller **13820** responsive to the CTR signal **002** and to a multiple wavelength mapping table **13810** downloaded from the switch controller **13730** through control line **13735**, and a tunable multiple wavelength conversion subsystem **13850** responsive to a Color signal **13840** from the MWLC scheduling controller **13820**.

The tunable multiple wavelength conversion subsystem **13850** within the multiple WLC subsystem **13800** is connected to the output line **13710** of a respective one of the optical alignment subsystems **10900** from which the tunable multiple wavelength conversion subsystem **13850** receives an optical signal comprising a plurality of wavelengths. During each time frame of the CTR the tunable multiple wavelength conversion subsystem **13850** is tuned by the Color control signal **13840** to convert a first selected set of wavelengths, i.e., colors, into a second selected set of respective wavelengths emitted on the output line **13720**.

Each wavelength in the second selected set of wavelengths emitted on the output line **13720** of the tunable multiple wavelength conversion subsystem **13850** as a result of the conversion of the first set of wavelengths received on its input line **13710** carries the same information as the respective wavelength in the first set of wavelengths.

In a possible embodiment the color control signal **13840** in FIG. 22A selects a different first set of wavelength for conversion by the tunable multiple wavelength conversion subsystem **13850** during each time frame. In a possible embodiment the tunable multiple wavelength conversion subsystem **13850** converts the first selected set of wavelengths into a second fixed set of wavelengths during each time frame. In an alternative embodiment the tunable multiple wavelength conversion subsystem **13850** converts the first selected set of wavelengths into a second set of wavelengths that can be different during each time frame. In another alternative embodiment the first and the second selected set of wavelengths do not change over time, but the

mapping between each wavelength in the first selected set of wavelengths and the corresponding wavelength in the second selected set of wavelengths is changed during each time frame.

FIG. 22B is a sample timing diagram describing the operation of the second alternative embodiment of tunable wavelength conversion subsystem **13850**. The timing diagram shows a sequence of CTR time frames **TF** and for each time frame a first fixed selected set of wavelengths on data line **13710** being converted into a second fixed selected set of wavelengths emitted on data line **13720**, wherein each wavelength is identified by the color (green, red, and blue) of the corresponding light beam. For example, in the leftmost time frame shown in the timing diagram depicted in FIG. 22B the green wavelength is converted into the blue wavelength, the blue wavelength is converted into the red wavelength, and the red wavelength is converted into the green wavelength, i.e., during the leftmost time frame the blue light beam on data line **13720** carries the same information as the green light beam on data line **13710**, the red light beam on data line **13720** carries the same information as the blue light beam on data line **13710**, the green light beam on data line **13720** carries the same information as the red light beam on data line **13710**.

In an alternative embodiment the color control signal **13840** selects a different wavelength for conversion by the tunable wavelength conversion subsystem **13850** during each sub-time frame.

As shown in FIG. 22A, the Color control signal **13840** is generated by the multiple WLC scheduling controller **13820** according to the content of the multiple wavelength mapping table **13810** that indicates the wavelength mapping, i.e., into which outgoing wavelength each incoming wavelength is to be converted, during each TF. In a possible embodiment the wavelength mapping has a predefined pattern that is repeated every time cycle and super cycle. The mapping information contained in the multiple wavelength mapping table **13810** determines the route within the switching system **13700** of the data units carried over the plurality of optical

channels during each time frame. In a possible embodiment the content of the multiple wavelength mapping table **13810** is updated whenever a FLP is created or torn down.

In a possible embodiment, the above mentioned mapping repeats each time cycle or each super cycle.

An alternative embodiment features a centralized multiple WLC scheduling controller that generates the color control signal **13840** for all the tunable multiple wavelength conversion subsystems **13800** in the respective switching system **13700** as depicted in FIG. 21. In a possible implementation of such an embodiment the centralized multiple WLC scheduling controller is within the switch controller **13730**.

The WGR **13740** in the switching system **13700** architecture depicted in FIG. 21 couples each wavelength on the output line of each multiple WLC subsystem **13800** with the same wavelength on a selected fixed respective output **10020** of the switching system **13700**. Consequently, the second wavelength into which an incoming first wavelength is converted by the multiple WLC subsystem **13800** determines the routing of data units received on the first wavelength, i.e., the output **10020** on which the data units are transmitted. Consequently, data units received through a switch input **10010** can be forwarded on any output **10020**. However, due to the architecture of the switching system **13700**, during each time frame only data units carried on one wavelength can be transferred to a given output **10020**. In other words, it is not possible to transfer to the same output **10020** data units received on two different wavelengths carried on the same input fiber.

In order to transfer data units carried on a first wavelength to a first output **10020**, the selected multiple WLC subsystem **13800** connected through its respective line **13710** to the optical alignment subsystem **10900** of the first input **10010** is to be tuned to convert the first wavelength to a second selected wavelength such that the WGR **13740** switches the second

wavelength on the respective output line **13720** of the selected multiple WLC subsystem **13800** to the first output **10020.**

In a possible embodiment the switching system **13700** architecture shown in FIG. 21 does not provide multicast transmission capability in that it is not possible to transmits on more than one output **10020** data units received on the same wavelength of a first input **10010.**

In an alternative embodiment the switching system **13700** architecture shown in FIG. 21 provides multicast transmission capability thanks to the deployment of an embodiment of multiple WLC subsystem **13800** capable of converting at least one selected wavelength on its input line **13710** into at least two selected wavelengths on its output line **13720.** The WGR **13740** interconnecting the plurality of multiple WLC subsystems **13800** to the outputs **10020** of the switching system **13700** routes the two selected wavelengths to different outputs.

Multicasting from a first input **10010** to a first set of outputs **10020** is achieved by tuning during a first time frame the multiple WLC subsystem **13800** coupled to the first input **10010** to convert a first wavelength to a first set of wavelengths such that the WGR **13740** routes each wavelength in the first set of wavelengths on a respective one of the outputs **10020** of the first set of outputs.

FIG. 23A shows a possible architecture **13900** for a tunable multiple wavelength conversion subsystem **13850** that can be used in the multiple WLC subsystem **13800** within the switching system **13700** presented in FIG. 21. The tunable multiple wavelength conversion subsystem **13900** in FIG. 23A comprises a tunable multiple wavelength converter (TMWLC) **13910** responsive to the color control signal **13840** from the multiple WLC scheduling controller **13820.** The color control signal **13840** indicates the mapping for each wavelength to be converted by the TMWLC **13910.** The TMWLC **13910** receives an optical signal on line **13710,** such optical signal possibly comprising a plurality of wavelengths.

In a possible embodiment, the TMWLC **13910** converts the first set of wavelength channels identified by the color control signal **13840** into a second set of wavelength signals on line **13720** coupled to a respective one of the input lines of the WRG **13740**.

In the preferred embodiment of the present invention the color control signal **13840** selects a different set of wavelengths (colors) for being converted by the TMWLC **13910** during each time frame. In an alternative embodiment the color control signal **13840** selects a different set of wavelengths for conversion by the TMWLC **13910** during each sub-time frame. The multiple WLC scheduling controller **13820** controls the color signal **13840**, and ultimately the TMWLC **13910** responsive to the CTR **002** and to the multiple wavelength mapping table **13810** shown in FIG. 22A.

FIG. 23B shows the architecture of an alternative embodiment **13950** of tunable multiple wavelength conversion subsystem **13850** that can be used in the multiple WLC subsystem **13800** in FIG. 22A within the switching system **13700** presented in FIG. 21. The multiple tunable wavelength conversion subsystem **13950** in FIG. 23B comprises a wavelength division de-multiplexer (WDD) **10040**, a wavelength division multiplexer (WDM) **10050**, and a plurality of tunable wavelength conversion subsystems (TWLCS) **13150**, one for each output **13920** of the WDD **10040** and respective one of the inputs **13930** of the WDM **10050**. The TWLCSs **13150** can be implemented according to at least one of the embodiments presented in FIG. 16A, FIG. 17A, FIG. 18A, and FIG. 18C.

Each one of the wavelengths (e.g., green, blue, and red in the example depicted in FIG. 23B) comprised in the optical signal received on input line **13710** is separated by the WDD **10040** on a respective one of its outputs **13920**. During each time frame, each one of the TWLCS **13150** converts the fixed wavelength received from its respective input **13920** in a selected wavelength emitted on its respective output **13930**, responsive to the color signal **13840** from the MWLC scheduling controller **13820**.

In generating the color signal **13840** the MWLC scheduling controller **13820** depicted in FIG. 22A ensures that during each time frame the wavelengths emitted by the plurality of TWLCSs **13150** are all different from each other in order to avoid conflicts on the output **13720** of the WDM **10050**.

In the preferred embodiment of the present invention the color control signal **13840** selects a different set of wavelengths (colors) for being emitted by the TWLCSs **13150** and mapping with the corresponding incoming wavelengths during each time frame. In an alternative embodiment the color control signal **13840** selects a different set of wavelengths for being emitted by the TWLCSs **13150** and mapping with the corresponding incoming wavelengths during each sub-time frame. The multiple WLC scheduling controller **13820** in FIG. 22A controls the color signal **13840**, and ultimately the TWLCSs **13150** responsive to the CTR **002** and to the multiple wavelength mapping table **13810**.

The TWLCS **13150** can be implemented according to at least one of the embodiments disclosed in the present document in FIG. 16A, FIG. 17A, FIG. 18A, and FIG. 18C.

FIG. 26A shows the architecture of an alternative embodiment **14100** for a multiple tunable wavelength conversion subsystem **13850** that can be used in the multiple WLC subsystem **13800** within the switching system **13700** presented in FIG. 21. When the embodiment **14100** shown in FIG. 26A is deployed, the switching system **13700** has multicast capability.

The multiple tunable wavelength conversion subsystem **14100** comprises a star coupler **13010**, a WDM multiplexer (WDM) **10050**, and a plurality of tunable wavelength conversion subsystems (TWLCS) **13150**, one for each output **14110** of the star coupler **13010** and respective one of the inputs **13930** of the WDM **10050**.

The optical signal received on input line **13710** together with each one of the wavelengths (e.g., green, blue, and red in the example depicted in FIG. 23B) it comprises is replicated on each

output line **14110** of the star coupler **13150**. During each time frame, each one of the TWLCS **13150** converts a selected one of the plurality of wavelengths received from its respective input **14110** into a selected wavelength emitted on its respective output **13930**, responsive to the color signal **13840** from the MWLC scheduling controller **13820** depicted in FIG. 22A.

In generating the color signal **13840** the MWLC scheduling controller **13820** ensures that during each time frame the wavelengths emitted by the plurality of TWLCSs **13150** are all different from each other in order to avoid conflicts on the output **13720** of the WDM **10050**.

In the preferred embodiment of the present invention the color control signal **13840** selects a first wavelength (color) for being converted and a second wavelength to be emitted by the each TWLCS **13150** during each time frame, the first wavelength to be converted into the second wavelength. FIG. 26B is a timing diagram showing a sample operation of a TWLCS **13150** as shown in FIG. 26A.

In an alternative embodiment the color control signal **13840** selects a first wavelength for being converted and a second wavelength to be emitted by the TWLCSs **13150** during each sub-time frame. The multiple WLC scheduling controller **13820** depicted in FIG. 22A controls the color signal **13840**, and ultimately the TWLCSs **13150** responsive to the CTR **002** and to the multiple wavelength mapping table **13810**.

The embodiment **14100** of multiple tunable wavelength conversion subsystem **13850** depicted in FIG. 26A enables multicasting capability in the switching system **13700** depicted in FIG. 21 since at least two of the plurality of TWLCSs **13150** within one multiple tunable wavelength conversion subsystem **14100** can be tuned to convert a first selected wavelength from the input line **13710** into a set of different selected wavelengths on their respective output lines **13930** during a selected time frame. The said set of different selected wavelengths are combined by the respective WDM **10050** on its respective optical output line **13720** and the WGR **13740** switches the different wavelengths to different respective outputs **10020**. Since the

set of different selected wavelengths carry the same information carried by the first selected wavelength, data units carried over the first selected wavelength through the respective input **10010** are forwarded through the different respective outputs **10020**, over a respective one of the wavelengths of the set of different selected wavelengths on each output **10020**.

Optical Programmable Delay System

In the optical domain data units flow at light speed through optical fibers and other transport media. In the optical domain memory is realized via optical fiber in which optical signals are stored for the time they take to cross the optical fiber. Consequently, the amount of data units stored and the time spent by data units inside the storage medium (i.e., the optical fiber) depend on the length of the fiber.

A random access memory in which data units can be stored for any amount of time regardless of the time spent in the memory by other data units, is approximated in the optical domain by using a number of different techniques. In the following two such techniques known in the art are briefly described: serial optical delay line and parallel optical delay line.

The architecture of a linear delay line, a.k.a. serial optical delay line, is shown in FIG. 34A. A plurality of taps **3410** are inserted at predefined intervals onto an optical fiber **3420**. The tap **3410** is an optical switch that can let an optical signal pass through along the fiber **3420** or switch it out **3430**. In order to better understand how a linear delay line works and the role of time, let us observe a data unit that was injected into the fiber **3420** at time *t=0*. In order to fetch this data unit at any later time the fiber should be filled with infinite number of taps **3410**. Obviously, this is not feasible. In a possible realization taps **3410** are placed in regular intervals that are equally spaced in time. Let us call this time interval T. Consequently, a data unit that was injected into the fiber at time *t=0* can be fetched from the fiber at times: $t=1 \cdot T, 2 \cdot T, 3 \cdot T$, etc. A serial optical delay line controller **3490** determines configures the taps **3410** through its bi-directional control lines **3493**, responsive to the amount of time data units are to spend inside the

optical delay line. The serial optical delay line controller **3490** receives control and status information from the taps **3410** through its bi-directional control lines **3493**.

The architecture of a parallel optical delay line, more widely known as fiber delay line (FDL), is shown in FIG. 34B. Fibers **3460** of different lengths are deployed to delay data units for different amounts of time. The delay experienced by data units in a parallel optical delay line has predefined granularity depending on the length difference between the fibers **3460**. The number of parallel fibers **3460** needed to realize a parallel optical delay line depends on the granularity and maximum storage time required. In a possible realization the length difference between fibers **3460** is constant such that the first fiber **3460-1** delays by $1 \cdot T$, the second fiber **3460-2** delays by $2 \cdot T$, the third fiber **3460-3** delays by $3 \cdot T$, and so on. The optical signal injected in the parallel optical delay line through the input **3440** is split by an optical splitter **3450** over the plurality fibers **3460**. Only one of the optical signals exiting the plurality of fibers **3460** is selected by an optical selector **3470** for emission on the output **3480** of the optical parallel delay line. The optical selector **3470** can be implemented by at least one of: a plurality of optical gates and an optical star, a plurality of optical gates and an optical multiplexer, an N-by-1 optical switch. A parallel optical delay line controller **3495** configures the optical splitter **3450** and the optical selector **3470** through bi-directional control lines **3497** and **3498**, respectively, responsive to the amount of time data units are to spend inside the optical delay line. The parallel optical delay line controller **3495** receives control and status information from the optical splitter **3450** and the optical selector **3470** through the bi-directional control lines **3497** and **3498**, respectively.

The Alignment Problem in FIG. 29 and FIG. 4

Each channel (*j*) of a plurality of incoming channels – possibly being an optical channel multiplexed with other channels on a single fiber – on a selected link (*i*) has a unique time reference (UTR(i)), as shown in FIG. 29, that is independent of the CTR **002**, also shown in FIG. 29.

A timing diagram description of the alignment operation is provided in FIG. 29. The alignment operation as performed by an alignment subsystem **10100** with the architecture shown in FIG. 4, follows the following principle:

TF Alignment of UTR(*i*) to UTC–with at least three TF queues **1550**–principle of operation: The same queue is not used simultaneously for:

1. Receiving data units from the serial link **10160** – responsive to Select-in signal **10120** received from the alignment scheduler controller **10110**, and
2. Forwarding data units to the switch through line **10165** – responsive to Select-out signal **10130** received from the alignment scheduler controller **10110**.

In the timing diagram example of FIG. 29 it is shown that a (sub)TF queue ((sub)TF Queue 1, (sub)TF Queue 2, (sub)TF Queue 3 - **1550**), shown in FIG. 4, is not written into and read from at the same time. In other words, the Select-in signal **10120** and the Select-out signal **10130** will not select the same TF queue at the same time.

In the example in FIG. 4, the TF duration deployed on channel **10160** j of link i is **TFi_j**. Time frames of the common time reference and the UTR-i are divided in sub-time frames of duration **subTF**. In the examples presented in this disclosure the same sub-time frame duration is deployed on all input channels **10160** and for transfers through the switch fabric; a different sub-time frame duration could be deployed on different channels and for transfers through the switch fabric. The time frame duration on channel (j) is indicated as TF in the timing diagrams depicted in FIG. 29.

The Alignment Problem in the Optical Domain

The alignment operation can be performed in the optical domain. FIG. 12 shows a first possible embodiment of optical alignment subsystem **10900** based on a programmable delay

system **10930** and comprising a delay controller **10990** further comprised of an optical alignment controller **10910** and a delineation controller **10920**. The programmable delay system **10930** delays the optical signal from the input **10010** to the output **10320**, responsive to the adjust delay control signal **10940**. The delineation controller **10920** is responsible to devise the unique time reference (UTR-i) associated to input i **10010**, and the optical alignment controller **10910** is responsible for determining, responsive to the CTR **002** and the UTR-i **10950**, the delay needed to align to the CTR data units received from the input **10010**.

Time frames on the input **10010** are aligned to the unique time reference (UTR) associated to the respective optical communication link I — UTR-i. The programmable delay system **10930** delays the optical signal received from the input **10010** in a way that time frames carried by the optical signal on the outgoing optical link **10320** are aligned with the common time reference (CTR). The optical programmable delay system **10930** can be realized, for example, through a serial optical delay line with multiple tap points - such as the one depicted in FIG. 34A - or through a fiber delay line comprising a plurality of fibers of different length - such as the parallel optical delay line depicted in FIG. 34B - or according to one of the embodiments presented below in this disclosure.

The amount of delay that the programmable delay system **10930** has to introduce depends on the phase difference between the CTR and UTR-i. This phase difference can change over time as a result of changes in the propagation delay over the communications link coupled to input i **10010** in FIG. 12. FIG. 28 shows an example of deployment of optical alignment subsystems **10900**. The output link **7220** of a first optical alignment subsystem **10900-1** is coupled to the input link **7230** of a second optical alignment subsystem **10900-2** through a variable delay network **7210** realized, for example, with at least, but not limited to, one of the following technologies: SONET, IP, MPLS, ATM, and Lambda Routing. The time frames on the output link **7220** of the first optical alignment subsystem **10900-1** are aligned to the CTR **002** but, due

to the delay experienced across the network **7210**, the time frames on the input link **7230** are not necessarily aligned to the CTR **002**. Moreover, since the delay experienced through the network **7210** is not constant, the phase difference between the CTR **002** and the UTR of the input link **7230** changes over time.

The delay introduced by the programmable delay system **2700** in the second optical alignment subsystem **10900-2** is such that the overall delay experienced by data units carried by the optical signal when traveling from the output link **7220** of the first optical alignment subsystem **10900-1** — through the variable delay network **7210**, the input link **7230** of the second optical alignment subsystem **10900-2**, and the programmable delay system **2700** of the second optical alignment subsystem **10900-2** — to the output link **7240** of the second optical alignment subsystem **10900-2** is an integer number of time frames.

According to the embodiment of optical alignment subsystem **10900** depicted in FIG. 12, the optical alignment controller **10910** compares the UTR-i and the CTR to determine the proper delay that the programmable delay system **10930** should introduce. The optical alignment controller **10910** in FIG. 12 adjusts the delay introduced by the programmable delay system **10930** through the adjust delay control signal **10940**. The optical alignment controller **10910** receives the CTR from an external device, such as, for example, a GPS receiver board, and the UTR-i through the UTR-i line **10950** from the delineation controller **10920**.

With reference to FIG. 12, the delineation controller **10920** devises the UTR-i directly from the optical signal received through the input **10010**. One way for the delineation controller **10920** to devise the UTR-i is through implicit or explicit time frame delimiters embedded in the flow of data units.

Explicit delimiters can be realized by at least one of a plurality of different methods. There can be a different delimiter control word to signal the beginning of a new TF (i.e., a time frame delimiter – TFD), time cycle (i.e., a time cycle delimiter – TCD) and super cycle (i.e., a

super cycle delimiter – SCD). The delimiter control word can be included in the stream of bits or symbols transmitted at the physical level, e.g., with an 8B/10B encoding. The explicit delimiter signaling can be realized by the SONET/SDH path overhead field that was designed to carry control, signaling and management information. Alternatively, the explicit delimiter signaling can be embedded in the PPP, HDLC, IP header, or in any protocol header exchanged over the communications links between switches. An implicit delimiter can be realized by measuring the UTR-i time with respect to the CTR. An alternative way of implementing an implicit delimiter is by counting the number of bytes from an explicit delimiter.

Alternatively, time frame delineation can be based on time frame delimiters in the optical signal carried on the communications link coupled to input i. A possible embodiment of optical time frame delimiter consists of dedicating one of the wavelengths of the communications link for transmission of the delimiter. The delineation controller **10920** detects the delimiters on the dedicated wavelength and devises the UTR-i. In an alternative embodiment the time frame delimiter are realized by introducing a gap, i.e., a period of dark, in the optical signal on the boundary between two adjacent time frames, as shown in FIG. 33. In other words, for each time frame, after having transmitted all the data units belonging to the time frame, the laser transmitter of each wavelength is turned off before starting transmitting data units belonging to the next time frame. The delineation controller **10920** detects the gaps on at least one of the wavelengths of the input **10010** and uses the derived timing information to devise the link's UTR.

By using at least one of the above mentioned explicit and implicit delimiters, the delineation controller **10920** is capable of devising the UTR-i from the information received from input line **10010** and of generating the corresponding UTR-i signal **10950.**

FIG. 30 shows a second possible embodiment of optical alignment subsystem **10900** based on an optical programmable delay system **10930** and comprising a delay controller **10990**

further comprised of an optical alignment controller **10910** and a delineation controller **10920.** The programmable delay system **10930** delays the optical signal from the input **10010** responsive to the adjust delay control signal **10940.** The delineation controller **10920** is responsible for devising the aligned unique time reference (aUTR-i) **10960** associated to outgoing optical link **10320** corresponding to input i **10010.** The optical alignment controller **10910** is responsible for determining, responsive to the CTR **002** and the aUTR-i **10960**, the delay needed to align to the CTR data units received from the input **10010**, i.e., to align the aUTR-i **10960** and the CTR **002.**

Time frames on the input **10010** are aligned to the unique time reference (UTR-i) associated to the respective optical communication link I — UTR-i. The programmable delay system **10930** delays the optical signal received from the input **10010** in a way that time frames associated to data units carried by the optical signal on the outgoing optical link **10320** constituting the aUTR-i, are aligned to the common time reference (CTR). The optical programmable delay system **10930** can be realized, for example, through through an optical delay line with multiple tap points (a.k.a. linear optical delay line)- such as the one depicted in FIG. 34A - or through a fiber delay line comprising a plurality of fibers of different length (a.k.a. parallel optical delay line) - such as the parallel optical delay line depicted in FIG. 34B - or according to one of the embodiments presented below in this disclosure (see FIG. 27, 31, 32, and 35).

The amount of delay that the programmable delay system **10930** has to introduce depends on the phase difference between the CTR and aUTR-i, i.e., ultimately the phase difference between CTR and UTR-i. This phase difference can change over time as a result of changes in the propagation delay over the communications link coupled to the input i **10010.** The optical alignment controller **10910** compares the aUTR-i and the CTR to determine the proper delay that the programmable delay system **10930** should introduce in order to keep the aUTR-i signal **10960** aligned to the CTR **002.** The optical alignment controller **10910** adjusts the delay

introduced by the programmable delay system **10930** through the adjust delay control signal **10940**. The optical alignment controller **10910** receives the CTR signal **002** from an external device, such as, for example, a GPS receiver board, and the aUTR-i through the aUTR-i line **10960** from the delineation controller **10920**.

The delineation controller **10920** devises the aUTR-i directly from the optical signal transported by the outgoing optical link **10320**. One way for the delineation controller **10920** to devise the aUTR-i is through implicit or explicit time frame delimiters embedded in the flow of data units. Explicit delimiters can be realized by one of a plurality of different methods. There can be a different delimiter control word to signal the beginning of a new TF (i.e., a time frame delimiter – TFD), time cycle (i.e., a time cycle delimiter – TCD) and super cycle (i.e., a super cycle delimiter – SCD). The delimiter control word can be included in the stream of bits or symbols transmitted at the physical level, e.g., with an 8B/10B encoding. The explicit delimiter signaling can be realized by the SONET/SDH path overhead field that was designed to carry control, signaling and management information. Alternatively, the explicit delimiter signaling can be embedded in the PPP, HDLC, IP header, or in any protocol header exchanged over the communications links between switches. An implicit delimiter can be realized by measuring the UTR-i time with respect to the CTR. An alternative way of implementing an implicit delimiter is by counting the number of bytes from an explicit delimiter.

Alternatively, time frame delineation can be based on time frame delimiters in the optical signal carried on the communications link coupled to input i. A possible embodiment of time frame delimiter consists of dedicating one of the wavelengths of the communications link for transmission of the delimiter. The delineation controller **10920** detects the delimiters on the dedicated wavelength and devises the aUTR-i. In an alternative embodiment time frame delimiters are realized by introducing a gap, i.e., a period of dark, in the optical signal on the boundary between two adjacent time frames, as shown in FIG. 33. In other words, for each time

frame, after having transmitted all the data units belonging to the time frame, the laser transmitter of each wavelength is turned off before starting transmitting data units belonging to the next time frame, as shown in FIG. 33. The delineation controller **10920** in FIG. 30 detects the gaps on at least one of the wavelengths of the outgoing optical link **10320** and uses the derived timing information to devise the aUTR-i corresponding to input link i **10010**.

Realization of an Optical Programmable Delay System

FIG. 34A shows a possible embodiment of optical programmable delay system **10930** based on a serial optical delay line comprising of an optical fiber **3420** interrupted by a plurality of tap points **3410** and a serial optical delay line controller **3490**. In the preferred embodiment tap points **3410** are equally spaced; the distance between two subsequent tap points **3410** determines the granularity with which the delay introduced by the serial optical delay line can be adjusted.

In the preferred embodiment the tap point **3410** is implemented by a 1-by-2 optical switch. In an alternative embodiment tap points **3410** can be realized by means of optical stars, a.k.a. optical splitters and star couplers. A serial optical delay line controller **3490** determines the delay experienced by an optical signal entering the serial optical delay line through the input optical fiber **3420** and being switched by a selected one of the tap point **3410** to its output **3430** by selecting, through control signals **3493**, one of the 1-by-2 optical switches for connecting its input with its output **3430**. The serial optical delay line controller **3490** operates responsive to the adjust delay control signal **10940** that is also called length signal since it modifies the length of the fiber traveled by optical signals traversing the optical delay line.

FIG. 34B shows a possible embodiment of fiber delay line or parallel optical delay line comprising a plurality of different length optical fibers **3460-1** through **3460-N** coupled to an input fiber **3440** through an input coupling device **3450** and to an output fiber **3480** via an output coupling device **3470**. The input coupling device **3450** can be, but is not restricted to, a star

coupler, or a 1-by-N switch. The output coupling device **3470** can be, but is not restricted to, one of the following: a star coupler, a plurality of optical gates and a star coupler, an optical multiplexer, a plurality of optical gates and an optical multiplexer, an N-by-1 switch.

A parallel optical delay line controller **3495** determines the delay experienced by an optical signal entering the serial optical delay line through the input optical fiber **3440** and exiting through the output optical fiber **3480** by selecting one of the N parallel different length optical fibers **3460** through the control signals **3497** and **3498**. The parallel optical delay line controller **3495** operates responsive to the adjust delay control signal **10940** that is also called length signal since it modifies the length of the fiber traveled by optical signals traversing the optical delay line.

A possible alternative embodiment of the programmable delay system **10930** is shown in FIG. 27 and includes a programmable optical switching matrix **2730** with a plurality of input ports and output ports (numbered from **1** to **N**); a programmable delay controller 2720; a plurality of optical fibers **2740-2** through **2740-N**, each connecting one of the outputs to a respective one of the inputs, and an programmable delay controller **2720**. One or more optical fibers can have the same length or have different lengths, wherein fiber *i*'s length is given by $l_i = C\, t_i$, where C is the speed of light in the fiber and t_i is the delay introduced by the corresponding optical fiber.

By properly configuring input/output connections **2790** across the programmable optical switching matrix an optical signal entering the programmable delay system from a mater input **2710** connected to switch input 1 is delayed, i.e., buffered, until it exists from switch output 1 **2715**, for a time corresponding to the sum of the propagation delay through a subset of the said plurality of optical fibers. For example, when the input/output connections **2790-1** through **2790-4** in FIG. 27 are configured, the delay experienced by an optical signal traveling from the master input **2710** to the master output **2715** of the programmable delay system **10930** is $t_2+t_4+t_N$, as

expressed by the delay equation in FIG. 27. In other words, the optical programmable delay system **10930** presented in FIG. 27 provides a delay which is obtained as the sum of the time required by an optical signal to traverse an arbitrary subset of the plurality of optical fibers **2740** connecting the switch outputs to the switch inputs.

In the example configuration in FIG. 27, an optical signal entering the programmable delay system **10930** through its input **2710** is switched by input/output connection **2790-1** of the programmable optical switching matrix **2730** to output **2** and travels on the corresponding optical fiber **2740-2** to input **2**, where it is switched to output port **4** by the input/output connection **2790-2**. Then the optical signal enters optical fiber **2740-4** and travels to input **4** where it is switched to output port **N** by the input/output connection **2790-3**. After having traveled through optical fiber **2740-N**, the optical signal is switched to output port **1**, connected to the programmable delay system output **2715**, by the input/output connection **2790-4**.

The programmable delay controller **2720** configures the programmable optical switching matrix **2730** to provide the input/output connections **2790** required to introduce the required delay between input **2710** and output **2715** of the programmable delay system **10930**. The programmable delay controller **2720** can receive control and status information from the programmable optical switching matrix **2730**. The programmable delay controller **2720** operates responsive to the adjust delay control signal **10940** that is also called length signal since it modifies the length of the fiber traveled by optical signals traversing the programmable delay system **10930**.

In a possible embodiment, the length of each fiber in the set of fibers **2740** is chosen as a multiple of a base length, wherein the multiple is a power of 2. For example, if $C{\cdot}t_0$ is the base length, the length of each fiber in the set of N fibers can be chosen as $C{\cdot}t_0$, $2{\cdot}C{\cdot}t_0$, $2^2{\cdot}C{\cdot}t_0$, $2^{N-1}{\cdot}C{\cdot}t_0$. The choice of this set allows the delay imposed by the programmable delay system **10930** to be varied between 0 and $(2^N\text{-}1){\cdot}t_0$, with a granularity t_0. The total amount of fiber needed is $(2^N$-

1)$\cdot C\cdot t_0$, which is the amount required by a tap-based optical delay line, and much smaller than the amount required by a traditional parallel fiber delay line. Given a maximum delay D, the total number of switch inputs/outputs N required to provide a granularity t_0 is ceil[$\log_2$ceil(D/t_0+1)], where ceil(x) is a function returning the smallest integer greater than or equal to x. Notice that an optical signal delayed by an optical programmable delay system **10930** according to this embodiment traverses the programmable optical switching matrix at most N times, while the optical signal delayed by a serial optical delay line traverses D/t_0 taps. In other words, assuming that a tap introduces the same attenuation as a programmable optical switching matrix (they are both switches), the attenuation (measured in dB) introduced by an optical programmable delay system **10930** according to this embodiment is roughly the base 2 logarithm of the attenuation (measured in dB) introduced by a serial optical delay line.

For example, given a basic delay t_0=80 ns, provided by 16 meters of fiber, and an 8-by-8 programmable optical switching matrix **2730**, an programmable delay system can be realized which provides a variable delay between 0 and 10 microseconds with a granularity of 80 ns. The resulting programmable delay system requires a total of 2,032 meters of fiber. The programmable optical switching matrix **2730** in FIG. 27 is traversed at most 8 times by an optical signal, while an equivalent serial optical delay line contains 256 taps. Given that the insertion loss of a tap is the same as the one of a programmable optical switching matrix, the power loss (measured in dB) of an optical signal traversing the presented embodiment of programmable optical delay system is (measured in dB) 8 times lower than the one introduced by a serial optical delay line.

FIG. 31 shows an alternative embodiment of optical programmable delay system **10930** based on a programmable optical switching matrix (POSM) **2730** and comprising a programmable delay controller **3120**, a plurality of wavelength converters (WLCs) **3150, 3153, 3155** connected to a subset of the switch inputs **3170, 3173,** and **3175** and outputs **3160, 3163,**

and **3165**, a plurality of wavelength division multiplexers (WDMs) **3130**, a plurality of wavelength division de-multiplexers (WDDs) **3110**, and a plurality of optical fibers **3140**, each one connecting the output of a WDM **3130** to the input of a WDD **3110**.

Deployment of WLCs **3150, 3153, 3155** enables an optical fiber to be traversed a plurality of times by the same data units, each time carried on a different wavelength. In the embodiment presented in FIG. 31, two WLCs (WLCg **3153** and WLCb **3155**) are connected to a respective input **3167** and **3161** of each WDM **3130**. Another embodiment uses two wavelengths and hence one WLC, e.g., WLCg **3153**, connected to a respective input **3167** of each WDM **3130**. An alternative embodiment uses a number of wavelengths *w* larger than 3 and hence *w*-1 WLCs are connected to the inputs of each WDM **3130**. In another embodiment the number of WLCs connected to each WDM **3130** is not the same for all the WDMs **3130**.

Each WLC converts an optical signal transmitted over a first predefined wavelength to an optical signal on a second predefined wavelength, wherein the optical signal before and after the conversion carry the same digital information.

As shown in the POSM connection example in FIG. 31, an optical signal entering the programmable delay system **10930** from its input **2710** on a first wavelength **r** is switched through input/output connection **3190-1** to POSM output **2**, which is not connected to a wavelength converter. The optical signal travels once through the respective optical fiber **3140-1**.

Then, input/output connection **3190-2** through the programmable optical switching matrix **2730** switches the signal, on a first wavelength **r**, to an output **3165** connected to a WLC (WLCg) **3153**. The signal will travel twice through the corresponding fiber **3140-2**. In fact, the WLC **3153** converts the incoming first wavelength **r** to an outgoing second wavelength **g** that is injected into the corresponding optical fiber **3140-2** by a corresponding WDM **3130**.

When exiting from the fiber **3140-2**, after the first travel, over the second wavelength **g** generated by WLCg **3153**, the optical signal is separated by WDD **3110** on input **3175** of the

programmable optical switching matrix **2730** and it is switched by input/output connection **3190-4** to an output **3163** connected to a WLC (WLCb) **3155**. The WLC WLCb **3155** converts the incoming second wavelength **g** to an outgoing third wavelength **b** that is injected on the corresponding optical fiber **3140-2** by a corresponding WDM **3130**.

After the second travel through the fiber **3140-2** over the third wavelength **b** generated by WLCb **3155**, the optical signal is separated by the respective WDD **3110** on output **3177** connected to a WLC (WLCr) **3150** that converts the incoming third wavelength **b** to an outgoing first wavelength **r** on a connection **3173** to the programmable optical switching matrix **2730**. Input/output connection **3190-6** switches the optical signal to an output **3160** connected to a WDM **3130** that injects the optical signal on a fiber **3140-N** on which, due to the input/output connections **3190-7** and **3190-8**, the optical signal is going to travel three times: as a first wavelength **r**, then as a second wavelength **g**, and finally as a third wavelength **b**. The optical signal exiting optical fiber **3140-N** over wavelength **b** is separated by the corresponding WDD **3110** on line **3177**, converted into wavelength **r** by WLCr **3150**, enters the programmable optical switching matrix **2730** through the optical line **3173** connected to input **3·N+1**, and, through the input/output connection **3190-5**, it reaches POSM output **1** that is connected to the output **2715** of the programmable delay system **10930**.

The delay introduced by the programmable delay system **10930** with the programmable optical switching matrix configuration shown in FIG. 31 **3190** is $t_1+2\cdot t_2+3\cdot t_N$.

The programmable delay controller **3120** in FIG. 31 is responsible for changing the configuration of the programmable optical switching matrix **2730** through control signal **3127**. In a possible embodiment, the WDDs **3110**, WDMs **3130**, and the wavelength converters WLCr **3150**, WLCg **3153**, and WLCb **3155** operate in a static way. In another embodiment, the programmable delay controller **3120** in FIG. 31 changes the configuration of the WDDs **3110**, of the WDMs **3130**, and of the wavelength converters WLCr **3150**, WLCg **3153**, and WLCb **3155**,

through control signals **3121, 3125, 3129, 3122,** and **3123**, respectively. The programmable delay controller **3120** can receive control information from the programmable optical switching matrix **2730**, the WDDs **3110**, the WDMs **3130**, and the wavelength converters WLCr **3150**, WLCg **3153**, and WLCb **3155**, through the bi-directional control signals **3127, 3121, 3125, 3129, 3122,** and **3123**, respectively. The programmable delay controller **3120** operates responsive to the adjust delay control signal **10940** that is also called length signal since it modifies the length of the fiber traveled by optical signals traversing the programmable delay system **10930**.

In a possible embodiment, the length of each fiber in the set of fibers **3140** is chosen as a multiple of a base length, wherein the multiple is a power of 2. For example, if $C \cdot t_0$ is the base length, the length of each fiber in the set of N fibers can be chosen as $C \cdot t_0$, $2^{\text{floor}[\log(w)]} \cdot C \cdot t_0$, $2^{\text{floor}[2 \cdot \log(w)]} \cdot C \cdot t_0$, ..., $2^{\text{floor}[(N-1) \cdot \log(w)]} \cdot C \cdot t_0$, where floor($x$) is a function returning the largest integer smaller than or equal to x, log(x) is a function returning the base 2 logarithm of x, and w+1 is the total number of wavelengths per optical fiber. The choice of this set allows the delay imposed by the programmable delay system **10930** to be varied between 0 and $(2^{\text{floor}[N \cdot \log(w)]}-1) \cdot t_0$, with a granularity t_0. The total amount of fiber needed is smaller than the amount required by the previous embodiments (e.g., the one shown in FIG. 27) of programmable delay system. The total number of POSM inputs (outputs) is $N \cdot (w+1)+1$.

For example, given a basic delay t_0=80 ns, provided by 16 meters of fiber, a 21-by-21 programmable optical switching matrix and five wavelengths (w=4) on each fiber **3140** enable the realization of a programmable delay system that provides a variable delay between 0 and 10 microseconds with a granularity of 80 ns. The resulting programmable delay system requires four fibers having an overall length of 1,360 meters, wherein the lengths of the four fibers are 16 meters, 16·4=64 meters, 16·16=256 meters, and 16*64=1,024 meters.

FIG. 32 shows an alternative embodiment of programmable delay system **10930** utilizing a programmable optical switching matrix (POSM) **2730** and multiple wavelengths on each fiber.

The embodiment of programmable delay system **10930** depicted in FIG. 32 comprises a programmable delay controller **3220**, a programmable optical switching matrix (POSM) **2730**, a plurality of wavelength converters (WLCr) **3150**, a plurality of multi-wavelength converters (MWLCs) **3250**, one for each optical fiber **3240** connecting a respective one of a plurality of WDMs **3230** to a respective one of a plurality of WDDs **3210**. Each MWLC **3250** converts a first selected one of a plurality of wavelengths (e.g., wavelength **g**, wavelength **b**, wavelength **r**) presented at its input **3265** into a second selected one of a plurality of wavelengths (e.g., wavelength **b**, wavelength **r**, wavelength **g**) emitted from its output **3263** in such a way that the digital information carried by the second selected wavelength is the same as the one carried by the first selected wavelength.

Deployment of MWLCs **3250** enables an optical fiber **3240** to be traversed a plurality of times by the same data units, each time carried on a different wavelength (e.g., wavelength **g**, wavelength **b**, wavelength **r**).

Given the POSM configuration shown in the example in FIG. 32, an optical signal entering the programmable delay system **10930** from its input **2710** is switched through input/output connection **3290-1** to a POSM output **3260** which is not connected to a MWLC **3250**. The optical signal travels once through the respective optical fiber **3240-1** and is separated by the corresponding WDD **3210** on POSM input **3270**.

Then, input/output connection **3290-2** through the programmable optical switching matrix **2730** switches the signal, on a first wavelength **r**, to an output **3260** where the optical signal is injected into a second optical fiber **3240-2** by the respective WDM **3230**. The signal will travel twice through the fiber **3240-2**.

When exiting from optical fiber **3240-2**, after a first travel on the first wavelength **r**, the optical signal is separated by the corresponding WDD **3210** on POSM input **3270**. The input/output connection **3290-4** through the programmable optical switching matrix **2730**

switches the signal to an output **3265** connected to a MWLC **3250** that converts the signal to an outgoing second wavelength **g** sent to the corresponding WDM **3230** through line **3263**. The WDM **3230** injects the second wavelength **g** into the optical fiber **3240-2** for a second travel. The optical signal travels for the second time through the respective optical fiber **3240-2** as wavelength **g** and it is separated by the corresponding WDD **3210** on line **3273** connected to a WLCr **3150** that converts the second wavelength **g** into an outgoing first wavelength **r** sent to switch input **3275**.

Input/output connection **3290-5** through the programmable optical switching matrix **2730** switches the signal, on the first wavelength **r**, to an output **3260** where the optical signal is injected into a third optical fiber **3240-N** by the respective WDM **3230**. The signal will travel three times through the fiber **3240-N**.

The optical signal exits optical fiber **3140-N** for the first time over the first wavelength **r** and is separated by the respective WDD **3210** on input **3270** of the programmable optical switching matrix **2730**. Through the input/output connection **3290-6** the optical signal is switched to output **3265** connected to a respective MWLC **3250** that converts the incoming first wavelength **r** to an outgoing third wavelength **b** emitted on line **3263**. A WDM **3230** injects the optical signal into the optical fiber **3240-N** and the optical signal propagates through it for the second time until it reaches the respective WDD **3210** that separates the third wavelength **b** on input **3270** of the programmable optical switching matrix **2730**.

Through the input/output connection **3290-6** the optical signal is switched to output **3265** connected to the respective MWLC **3250** that converts the incoming third wavelength **b** to an outgoing second wavelength **g** emitted on line **3263**. A WDM **3230** injects the optical signal into the optical fiber **3240-N** and the optical signal propagates through it for the third time until the respective WDD **3210** that separates the second wavelength **g** on line **3273** connected to a WLCr **3150**. The WLCr **3150** converts the second wavelength **g** to a first wavelength **r** emitted on line

3275 connected to input **2·N** of the programmable optical switching matrix **2730**. The optical signal is switched through input/output connection **3290-3** to output **1** of the programmable optical switching matrix **2730** connected to the output **2715** of the programmable delay system.

The delay provided by the programmable delay system **10930** with the programmable optical switching matrix configuration shown in FIG. 32 **3290** is $t_1+2\cdot t_2+3\cdot t_N$.

The programmable delay controller **3220** in FIG. 32 is responsible for changing the configuration of the programmable optical switching matrix **2730** through control signal **3227**. In a possible embodiment, the WDDs **3210**, WDMs **3230**, the wavelength converters WLCr **3150**, and MWLCs **3250** operate in a static way. In another embodiment, the programmable delay controller **3220** in FIG. 32 changes the configuration of the WDDs **3210**, the WDMs **3230**, the wavelength converters WLCr **3150**, and MWLCs **3250** through control signals **3221, 3225, 3229**, and **3223**, respectively. The programmable delay controller **3220** can receive control and status information from the programmable optical switching matrix **2730**, the WDD **3210**, the WDM **3230**, the wavelength converters WLCr **3150**, and MWLC **3250**, through the bi-directional control signals **3227, 3221, 3225, 3229**, and **3223**, respectively. The programmable delay controller **3220** operates responsive to the adjust delay control signal **10940** that is also called length signal since it modifies the length of the fiber traveled by optical signals traversing the programmable delay system **10930**.

In a possible embodiment, the length of each fiber in the set of fibers **3140** is chosen as a multiple of a base length, wherein the multiple is a power of 2. For example, if $C\cdot t_0$ is the base length, the length of each fiber in the set of N fibers can be chosen as $C\cdot t_0$, $2^{\text{floor}[\log(w)]}\cdot C\cdot t_0$, $2^{\text{floor}[2\cdot\log(w)]}\cdot C\cdot t_0$, …, $2^{\text{floor}[(N-1)\cdot\log(w)]}\cdot C\cdot t_0$, where floor($x$) is a function returning the largest integer smaller than or equal to x, log(x) is a function returning the base 2 logarithm of x, and w+1 is the total number of wavelengths per optical fiber. The choice of this set allows the delay imposed by the programmable delay system **10930** to be varied between 0 and $(2^{\text{floor}[N\cdot\log(w)]}-1)\cdot t_0$, with a

granularity t_0. The total amount of fiber needed is smaller than the amount required by the previous embodiments (e.g., the one shown in FIG. 27) of programmable delay system. The total number of POSM inputs (outputs) is $N{\cdot}2{+}1$, i.e., the size of the programmable optical switching matrix **2730** deployed in the embodiment presented in FIG. 32 is fixed—independent of the number of channels per optical fiber—and smaller than the size of the programmable optical switching matrix **2730** required in the embodiment presented in FIG. 31.

For example, given a basic delay t_0=80 ns, provided by 16 meters of fiber, and a 9-by-9 programmable optical switching matrix, if five wavelengths are used (w=4) on each fiber **3140**, a programmable delay system can be realized which provides a variable delay between 0 and 10 microseconds with a granularity of 80 ns. The resulting programmable delay system requires four fibers having an overall length of 1,360 meters, wherein the lengths of the four fibers are 16 meters, 16·4=64 meters, 16·16=256 meters, and 16*64=1,024 meters.

FIG. 35 shows an alternative embodiment of programmable delay system **10930** utilizing a programmable optical wavelength switching matrix (POWSM) **3510** and multiple wavelengths on each fiber. The embodiment of programmable delay system **10930** depicted in FIG. 35 comprises a programmable delay controller **3520**, a plurality of multi-wavelength converters (MWLCs) **3250**, one for each optical fiber **3240** connecting a respective one of the MWLCs **3250** to a respective one of programmable optical wavelength switching matrix (POWSM) **3510**. Each MWLC **3250** converts a first selected one of a plurality of wavelengths (e.g., wavelength **g**, wavelength **b**, wavelength **r**) presented at its input **3565** into a second selected one of a plurality of wavelengths (e.g., wavelength **r**, wavelength **g**, wavelength **b**) emitted from its output **3540** in such a way that the digital information carried by the second selected wavelength is the same as the one carried by the first selected wavelength.

Deployment of MWLCs **3250** enables any one of the plurality of optical fibers **3540** to be traversed a plurality of times by the same data units, each time carried on a different wavelength (e.g., wavelength **g**, wavelength **b**, wavelength **r**).

The POWSM **3510** deployed in this embodiment is capable of independently switching any wavelength channel received on any one of the plurality of optical fibers **3540** coupled to its inputs **1** through **N+1** to any of its outputs **1** through **N+1**. Wavelength channels switched from different POWSM inputs to a selected one of the POWSM outputs are multiplexed on the respective output line **2715** and **3540**.

With the POWSM configuration shown in the example in FIG. 35, the **r** wavelength comprised in an optical signal entering the programmable delay system **10930** from its input **2710** is switched through input/output connection **3590-1** to a POWSM output **3565** connected to a respective MWLC **3250**. The respective MWLC **3250** converts wavelength **r** into wavelength **g** emitted on the optical fiber **3540-1**. The optical signal travels once through the respective optical fiber **3540-1** as wavelength **g** and, when it reached POWSM input **2**, it is switched to output **3** by the input/output connection **3590-2**.

Wavelength **g** emitted on the respective line **3565** is converted by the respective MWLC **3250** into wavelength **b** that is injected in the optical fiber **3540-2** through which the optical signal travels a first time until the corresponding POWSM input number **3**. Input/output connection **3590-3** through the programmable optical wavelength switching matrix **3510** switches the optical signal, on wavelength **b**, to output **3** where the optical signal is sent through the respective line **3565** to a MWLC **3250** that converts it to an outgoing wavelength **r** injected into the optical fiber **3540-2** for a second travel of the optical signal. The optical signal travels for the second time through the respective optical fiber **3540-2** as wavelength **r**. Upon arrival to the corresponding input **3** the optical signal on wavelength **r** is switched to POWSM output **N+1** through input/output connection **3590-4**.

Here the optical signal on wavelength **r** is emitted on the respective line **3565** and wavelength **r** is converted by the corresponding MWLC **3250** into wavelength **g** that is injected on the optical fiber **4530-N** on which the optical signal is going to travel three times, first over wavelength **g**, then over wavelength **b**, and finally over wavelength **r**.

When the optical signal exits optical fiber **3140-N** for the first time over wavelength **g**, it is switched to POWSM output **N+1** by input/output connection **3590-5**. When the optical signal exits optical fiber **3140-N** for the second time over wavelength **b**, it is switched to POWSM output **N+1** by input/output connection **3590-5**. Finally, when the optical signal exits optical fiber **3140-N** for the third time over wavelength **r**, it is switched to POWSM output **1** by input/output connection **3590-6** and emitted on the programmable delay system output **2715**.

The delay provided by the programmable delay system **10930** with the programmable optical wavelength switching matrix configuration shown in FIG. 35 **3590** is $t_1+2\cdot t_2+3\cdot t_N$.

The programmable delay controller **3520** in FIG. 35 is responsible for changing the configuration of the programmable optical wavelength switching matrix **3510** through control signal **3525**. In a possible embodiment, MWLCs **3250** operate in a static way. In another embodiment, the programmable delay controller **3520** in FIG. 35 changes the configuration of the MWLCs **3250** through control signals **3523**. The programmable delay controller **3520** can receive control and status information from the programmable optical wavelength switching matrix **3510** and MWLC **3250** through the bi-directional control signals **3525** and **3523**. The programmable delay controller **3520** operates responsive to the adjust delay control signal **10940** that is also called length signal since it modifies the length of the fiber traveled by optical signals traversing the programmable delay system **10930**.

In a possible embodiment, the length of each fiber in the set of fibers **3540** is chosen as a multiple of a base length, wherein the multiple is a power of 2. For example, if $C\cdot t_0$ is the base length, the length of each fiber in the set of N fibers can be chosen as $C\cdot t_0$, $2^{\text{floor}[\log(w)]}\cdot C\cdot t_0$,

$2^{\text{floor}[2\cdot\log(w)]}\cdot C\cdot t_0, \ldots, 2^{\text{floor}[(N-1)\cdot\log(w)]}\cdot C\cdot t_0$, where floor($x$) is a function returning the largest integer smaller than or equal to x, log(x) is a function returning the base 2 logarithm of x, and w+1 is the total number of wavelengths per optical fiber. The choice of this set allows the delay imposed by the programmable delay system **10930** to be varied between 0 and $(2^{\text{floor}[N\cdot\log(w)]}-1)\cdot t_0$, with a granularity t_0. The total amount of fiber needed is smaller than the amount required by previous embodiments (e.g., the one shown in FIG. 27) of programmable delay system. The total number of POWSM inputs (outputs) is N+1, i.e., the size of the programmable optical wavelength switching matrix **3510** deployed in the embodiment presented in FIG. 35 is fixed—independent of the number of channels per optical fiber—and smaller than the size of the programmable optical switching matrix **2730** required in the embodiments presented in FIG. 31 and FIG. 32. However, the POWSM **3510** used in the embodiment presented in FIG. 35 must be capable of independently switching single wavelengths, while the POSMs **2730** deployed in the previous embodiments (FIG. 27, FIG. 31, and FIG. 32) switch to the same output all the wavelength carried on each one of the plurality of input fibers.

For example, given a basic delay t_0=80 ns, provided by 16 meters of fiber, and a 5-by-5 programmable optical wavelength switching matrix, if five wavelengths are used (w=4) on each fiber **3540**, a programmable delay system can be realized which provides a variable delay between 0 and 10 microseconds with a granularity of 80 ns. The resulting programmable delay system requires four fibers having an overall length of 1,360 meters, wherein the lengths of the four fibers are 16 meters, 16·4=64 meters, 16·16=256 meters, and 16*64=1,024 meters.

From the foregoing, it will be observed that numerous variations and modifications may be effected without departing from the spirit and scope of the invention. It is to be understood that no limitation with respect to the specific apparatus illustrated herein is intended or should be inferred. It is, of course, intended to cover by the appended claims all such modifications as fall within the scope of the claims.